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EFFECTS OF DESIGN AUTOMATION ON THE LEAD TIME OF THE WATER-TUBE BOILER PRESSURE SPARE PART PROCESS

Faculty of Engineering and Natural Sciences
Master of Science Thesis
November 2020

ABSTRACT

Atte Helin: Effects of Design Automation on the Lead Time of the Water-tube Boiler Pressure Spare Part Process
Master of Science Thesis
Tampere University
Master's Degree Programme in Mechanical Engineering
November 2020

In industrial design offices, a considerable share of hours is spent on designing already existing and proven solutions. Design hours spent on these solutions can be considerably decreased with the use of design automation.

Design automation was widely used, but for pressure spare part process, a design automation benefit analysis had not been performed. Therefore, the objective of this thesis was to study the lead time effects of design automation in water-tube boiler pressure spare part process. In the first part of the thesis, a literature review was carried out on process development and design automation. After the literature review, the research methodology of the research was defined. Lastly, prior to the research part, a review on water-tube boilers was conducted.

In the research part of the thesis, a case study on the lead time effects of a design automation system on the simplest pressure spare parts, tube bends, was performed. The first part of the case study was gathering the design knowledge required in the process. After the design knowledge had been gathered, an analysis on the current process was performed. The analysis included gathering of other required data and the mapping of the current process by using a swimlane diagram. After the process analysis, the design automation system was created. When the design automation system was verified functional, the process was redefined to include the design automation system. When the redefinition had been done, the process was piloted. The piloting was done on 5 randomly selected projects in simulated circumstances.

Based on the piloted projects, the redefinition of the process and the creation of the design automation decreased the lead time of the process by an average of 47 % in simulated circumstances. For the drawing creation process, the design automation system decreased the lead time by 77 %. These results can be considered guiding for other pressure spare parts.

Keywords: design automation, water-tube boiler, pressure equipment, spare part

TIIVISTELMÄ

Atte Helin: Suunnitteluautomaation vaikutukset vesiputkikattiloiden painelaitevaraosaprosessin läpimenoaikaan
Diplomityö
Tampereen yliopisto
Konetekniikan diplomi-insinöörin tutkinto-ohjelma
Marraskuu 2020

Suunnittelutoimistoissa huomattava osuus tunneista käytetään olemassa olevien ja toimiviksi todettujen ratkaisujen uudelleensuunnitteluun. Tuntien osuutta tällaisissa ratkaisuissa voidaan vähentää huomattavasti suunnitteluautomaation avulla.

Suunnitteluautomaatiota käytettiin laajasti, mutta sen hyötyjä painelaitevaraosissa ei oltu vielä analysoitu. Sen vuoksi diplomityön tavoitteena oli tutkia suunnitteluautomaation vaikutuksia vesiputkikattiloiden painelaitevaraosaprosessin läpimenoaikaan. Tutkimuksen ensimmäisessä osiossa suoritettiin kirjallisuuskatsaus prosessikehityksestä ja suunnitteluautomaatiosta. Kirjallisuuskatsauksen jälkeen määriteltiin tukimuksessa käytetty tutkimusmetodologia. Viimeiseksi ennen diplomityön tutkimusosuutta suoritettiin yleiskatsaus vesiputkikatilloihin.

Tutkimusosuudessa suoritettiin tapaustutkimus suunnitteluautomaatiojärjestelmän vaikutuksesta yksinkertaisimpien painelaitevaraosien, eli putkitaivutusten, varaosaprosessin läpimenoaikaan. Tapaustutkimuksen ensimmäisessä osiossa kerättiin yhteen suunnitteluprosessissa tarvittava suunnittelutietämys. Seuraavaksi suoritettiin prosessianalyysi, jossa kerättiin yhteen prosessissa tarvittava muu data sekä luotiin uimaratakaavio alkuperäisestä varaosaprosessista. Prosessianalyysin jälkeen luotiin painelaitevaraosille sopiva suunnitteluautomaatiojärjestelmä. Kun suunnitteluautomaatiojärjestelmä oli todennettu toimivaksi, prosessi määriteltiin uudelleen. Viimeisenä uudelleenmäärityksen jälkeen suoritettiin prosessin pilotointi. Pilotointi suoritettiin viidellä satunnaisesti valitulla projektilla simuloiduissa olosuhteissa.

Pilotoinnin perusteella uudelleenmääritetty prosessi ja suunnitteluautomaatiojärjestelmän luonti laskivat prosessin läpimenoaikaa simuloiduissa olosuhteissa keskimäärin 47 %. Piirustuksen luontiprosessin läpimenoaika laski keskimäärin 77 %. Näitä tuloksia voidaan pitää suuntaa antavina myös muille painelaitevaraosille.

Avainsanat: suunnitteluautomaatio, vesiputkikattila, painelaite, varaosa

PREFACE

This thesis project was carried out from late 2019 to late 2020 for the Valmet's energy spare part team to analyze the benefits of design automation on the spare part process. During this process, I got to use and intensify my knowledge and to create and optimize my first design automation system.

To begin with, I want to thank my examiners Tero Juuti and Jarkko Pakkanen for the comments and examining my thesis on a quick schedule. From Valmet, I want to thank the energy spare part team management for giving me the possibility to work and do my thesis as a part of the great team. Thanks to the amazing colleagues I got to work with during the 3 years of work besides my studies. A special thank you to my supervisors Nanna Jaakkola and Juho Saarela for the competent assistance during the thesis process.

The prolonged studies in Tampere University of Technology and Tampere University have been part of the best years of my life so far. I am grateful to all the people who I got to make friends with besides my studies.

With my studies coming to an end, at least for now, I want to thank my parents for all their support during these years. Your example and support has always motivated me forward.

Last, I want to thank Laura for the immeasurably valuable support and for being the wonderful person you are.

This has truly been a period of time to remember.

Tampere, 9.11.2020

Atte Helin

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

API	Application Programming Interface
BFB	Bubbling fluidized bed
BPR	Business process re-engineering
CAD	Computer-aided design
CEN	French: Comité Européen de Normalisation, European Committee for Standardization
CENELEC	French: Comité Européen de Normalisation Électrotechnique, European Committee for Electrotechnical Standardization
CFB	Circulating fluidized bed
DFD	Data flow diagram
DMS	Document management system
ERP	Enterprise resource planning
Na_2S	Sodium sulfide
PED	Pressure Equipment Directive
PDM	Product data management
PLM	Product lifecycle management
RB	Recovery boiler
PI	Performance indicator
VBA	Visual Basic for Applications

d_i	Tube inner diameter
d_o	Tube outer diameter
e_{act}	Actual thickness at the extrados
e_{ext}	Minimum thickness at the extrados
e_t	Nominal tube thickness
r_b	Bending radius
u	Departure from circularity
u_{max}	Maximum departure from circularity

1. INTRODUCTION

According to Sunnersjö (2016 p. 3), in industrial design offices 70-90 % of working hours are used on redesigning already existing and proven basic design solutions. The percentage of hours used on redesigning can be reduced significantly by automation of the design process. In most cases, design automation provides value for both, the company, and the customer. The value for the company can, for example, be cost-saving or time-saving for more creative work over routine design assignments. In studies, significant savings have been reported after implementing a design automation system. For example, Lowe & Hartman (2011 p. 5) have reported that implementing a computational fluid dynamics design automation system reduced the design lead time by up to 99 % compared to the old process. For the customer, the value can, for example, be shorter delivery times. In the boiler business, an unexpected shutdown can cause significant costs to the operator of the boiler. According to Pratima (2016), in the United States a recovery boiler shutdown for a single recovery boiler pulp mill can cause an average production loss of $ 300 000 per day. Thus, short delivery times for spare parts can, at least in urgent shutdowns, be considerable cost-saving for the customer.

Even though new boiler pressure parts are getting increasingly standardized, in older boilers pressure parts differ from one boiler to another. Therefore, producing standardized pressure spare parts to all existing boilers is impossible. The design of pressure parts slightly varies in different boilers, but the basic design principles remain the same in every design process. Design tasks like these are highly suitable for automated design (Sunnersjö 2016 p. 19).

1.1 Research Background

Water-tube boiler pressure spare parts have not been subject to research at least from the maintenance point of view. Public research about boiler spare parts is also very limited. Jaakkola (2016) has discussed bubbling fluidized bed (BFB) boiler spare part management in her thesis. Rinkinen (2017) has discussed the criticality of spare parts in fluidized bed boilers in his thesis. Boiler maintenance has been discussed in literature by Vakkilainen (2017), Heselton (2014) and Woodruff et al. (2017). However, these publications do not go into detail about pressure part maintenance or spare parts. Research of design automation use in similar cases is also limited. Lowe & Hartman (2011) have discussed design automation with a case study in computational fluid dynamics. Sunnersjö (2016) has presented a few case studies in larger design automation system projects.

This research has been done for Valmet Technologies Oy. Valmet Technologies Oy is part of Valmet Oyj, which is a public listed company with over 13 000 employees around the globe. Valmet's offering includes automation, service and technologies for pulp mills, tissue, board and paper production lines and power plants. (Valmet Oyj 2020c) Services, the business line which includes spare parts, is the largest business line within Valmet with a net sale of 1,374 million euros and more than 6000 employees in 2019. (Valmet Oyj 2020a)

Design automation is used within the company, but it has not yet been implemented in the energy spare part business. The nature of water-tube boiler spare parts is different to other spare part businesses and a proper benefit analysis of design automation has not been implemented. The main objective of the thesis is identifying the lead time effects of automated manufacturing drawing design in water-tube pressure spare part business. The discussed process was defined to start from the customer inquiry or lead and to end when the order confirmation is sent to the customer. The definition was done because the design automation system creation only affects that part of the process. The objectives, deliverables and measures of the thesis are visualized in figure 1.

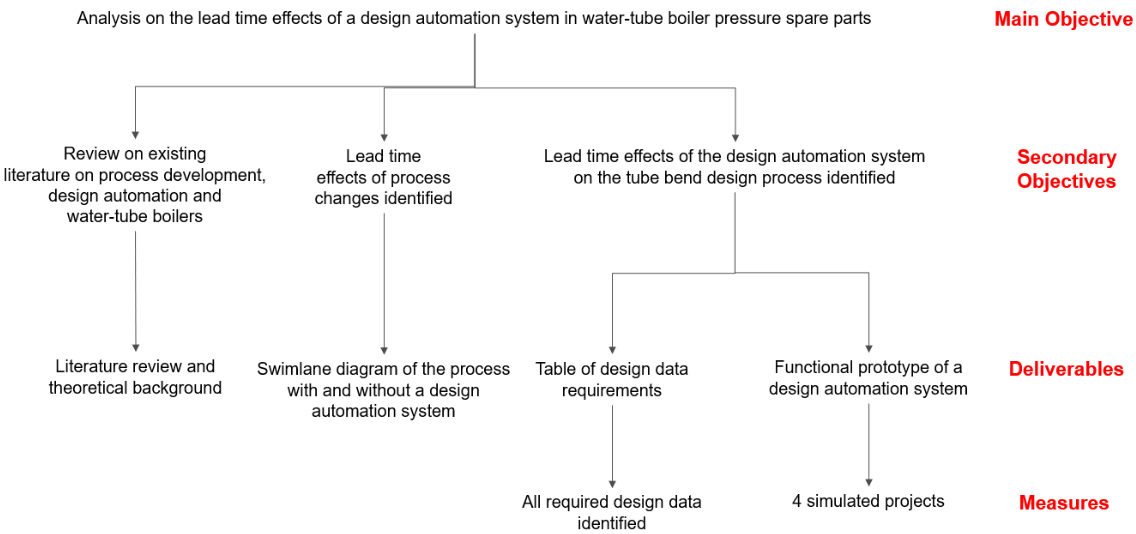


Figure 1. *Goal breakdown structure of the thesis.*

Focus of the thesis is on pressure spare parts of three different boilers: BFB boilers, circulating fluidized bed (CFB) boilers and recovery boilers (RB). Analyzed pressure spare parts are manufactured according to European Pressure Equipment Directive

(PED) (2014/68/EU). All the other pressure equipment laws are excluded from this thesis.

1.2 Research Questions

Based on the defined objectives of the thesis, a main research question was created to support the main objective. The main research question is:

- How does creation of a design automation system affect the lead time of the pressure spare part process? (RQ 1)

By answering this main research question, the main objective of this thesis is met. To support the main research question, also secondary questions were formulated. These secondary research questions are:

- What is the current state of the pressure spare part process? (RQ 1.1)
- What are the potential process changes if a design automation system is implemented? (RQ 1.2)
- How to create a design automation system that is suitable for the pressure spare part process? (RQ 1.3)

Research questions 1.1 and 1.2 are essential in analyzing the potential lead time effects of process changes. Question 1.3 is formulated to support the creation of the design automation system and to analyze the lead time effects of the design automation.

1.3 Research Structure

This thesis is divided into 9 chapters. These chapters go through the secondary objectives listed in figure 1. The secondary objectives are completed in chapters 2, 4 and 5. Chapter 5 presents a thorough answer to research questions 1.1, 1.2 and 1.3. Chapter 6 presents the achieved lead time effects with process changes and design automation system creation. Therefore, main objective is completed in chapter 6. Chapter 6 also answers the main research question RQ 1.

More accurately, chapter 2 goes through the basics of process development to provide a better understanding on how development of processes is done. After the process development, basics of design automation are covered to provide an insight on why design automation is used, and in which applications. The process development methods and design automation system creation methods presented in this chapter are used later in chapter 5.

In chapter 3, the research methodology is explained. This chapter will go through the rationale of the research choices in the research and explain the used methodologies. These choices include research basics: philosophy, approach, methodological choices, strategy, and data collection and processing methods.

Chapter 4 presents the basics of bubbling fluidized bed boilers, circulating fluidized bed boilers and recovery boilers. The chapter gives a brief understanding on what these boilers are used for, how do they operate, what is steam-water circulation, what are boiler pressure parts, what is the pressure part legislation and how is the maintenance performed in these boilers.

In chapter 5, the actual case study is presented. In this chapter, the studied products, tube bends, are introduced in order to understand the spare part process better. After the product has been introduced, the design knowledge required in the process is identified. Then a process analysis of the current process is performed. When the process is analyzed, the design automation system is created. After a draft design of the design automation system is finished, the process is redefined. Finally, the process is piloted in simulated circumstances.

Chapter 6 presents the achieved results with the redefined process. The results consist of the achieved lead time effects in the piloted projects.

Chapter 7 includes the discussion of the study. First, the results are discussed. In the discussion, a closer look is taken at the error sources and the reliability of the results. Then the answers to the research questions are presented and an evaluation of the study is performed. The evaluation provides an insight on the success of the research, suitability of the used research methodology, how the research could have been improved and what were the limitations on the research.

In chapter 8, an action proposal for the future is presented. In the first part of the chapter, the suggested actions for the company are presented. After that, ideas of topics for future research are discussed. Finally, in chapter 9 the thesis is concluded.

2. LITERATURE REVIEW

In this chapter, an overview of process development and design automation is provided. Understanding of process development and design automation are essential in order to understand objectives and used techniques in chapter 5. Section 2.1 consists of process development theories and techniques. First, basics of process development are presented. After the basics of process development, an overview on business process re-engineering is presented in section 2.1.1. In section 2.1.2, process mapping techniques are discussed in order to find a suitable technique for the development process. Section 2.1.3 provides a brief introduction to lead time as a process performance indicator and Lean tactics to improve lead time of processes. In section 2.2, possible benefits of the design automation use are discussed. Section seeks for designs, in which use of design automation is beneficial. After the applications and benefits are identified, techniques for design automation system planning and life cycle management of a design automation system are presented. The techniques for process development and design automation system creation are utilized in the research part of the thesis.

2.1 Process Development

The keywords used to find the references for this section were combined of "process development", "process mapping", "business process", "process development", "Lean", "lead time", "business process re-engineering", "business process reengineering" and "BPR". The main search tool was Andor, which is the search engine created by the Tampere University. In addition, Scopus, SpringerLink and IEEE databases were used to find more references. The results were arranged by their relevance and filtered to be preferably peer reviewed articles, books and journals from 2005 to 2020. The references were mainly chosen by previewing the title and abstract. If they seemed appropriate to what was being searched, the table of contents was previewed. After that, a selection was made whether to use it as a reference or not. Some of the references were also found from other similar publications.

Several definitions for processes exist. Martinsuo and Blomqvist (2010 p. 4) define processes as chains of events, that require resources to create added value to the customer. Sharp and Mcdermott (2009 p. 38) define a business process as "a way for an enterprise to organize work and resources (people, equipment, information, and so forth) to accomplish its aims". According to Martin and Osterling (2012 p. 1), a process is "a sequence of activities performed to design, produce, or deliver a good or service to an internal or external customer”. In the process definition by Martinsuo and Blomqvist (2010 p. 4), only value-adding processes are noted. However, in the definition by Martin and Osterling (2012 p. 1-2) also non-value adding processes are presented.

Development of processes is essential in the progress of businesses. A widely accepted approach in process performance improvement is reengineering them based on the best practices. This can also include adoption of information systems used in the best practices to own processes. (Bider & Johannesson 2005) According to Bradley’s (2015 p. 71) book focused on Lean, the quickest way to reduce wasteful lead time is to remove an entire step from a process.

In the flow concept of production, development is achieved through eliminating the unnecessary from production. Unnecessary, in flow concept of production, is defined as non-value adding activities or waste. By removing the non-value adding activities, the production process can be developed. (Koskela 2000 p. 54-56) Koskela (2000 p. 56) has identified 6 principles, which can be utilized to improve production. These are:

1. Reducing the share of non-value adding activities.
2. Reducing lead time.
3. Reducing variability.
4. Simplifying by minimizing the number of steps, parts and linkages.
5. Increasing flexibility.
6. Increasing transparency.

Martinsuo and Blomqvist (2010 p. 6) present that the profitability of processes can be developed in multiple ways. These ways can, for example, be implementation of a new process or implementing a radical change in an existing process. However, similar general steps can be identified in these variations. These general steps are illustrated in figure 2.

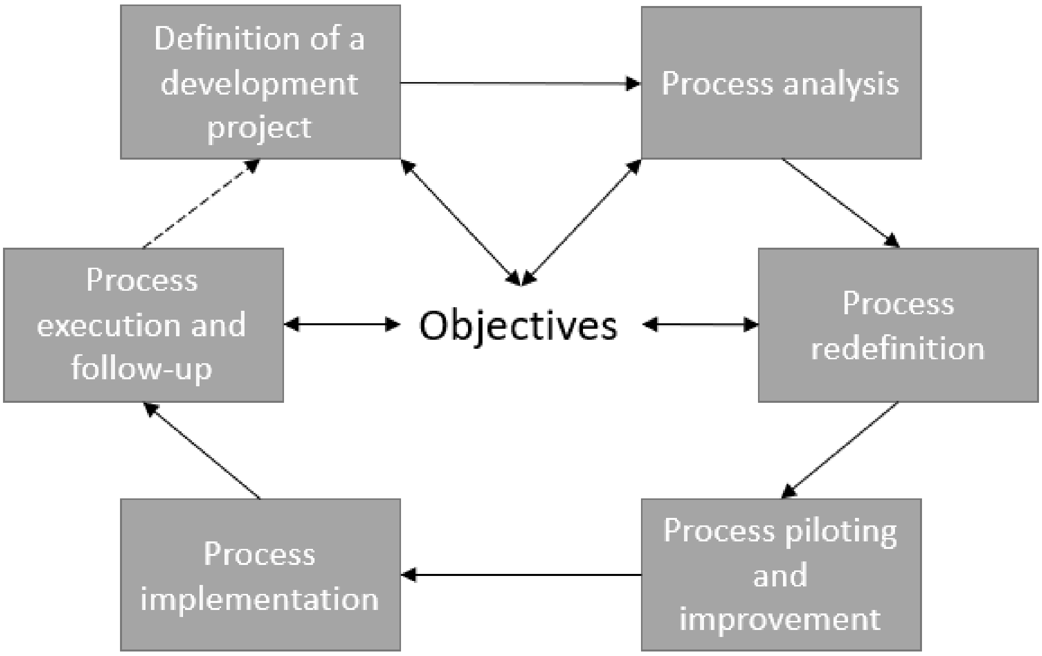


Figure 2. *General steps of process development. (adapting Martinsuo & Blomqvist 2010 p. 6)*

The first step of process development is an analysis of the current process. In the beginning, the processes or parts of a process, which are being developed in the development project are defined. When the definition has been done, all reliable information of the process is gathered. In case the developed process is an existing process, the gathered information should be measured data and information on how to illustrate the operation of the process. To gather the information, for example, interviews, workshops and process simulations can be utilized. The current state of the process should always be compared to the objectives. (Martinsuo & Blomqvist 2010 p. 6-7)

After the analysis has been performed, the areas in which the process can be developed, are identified. On some occasions, the whole process must be redefined. However, in most cases, the redefinition only covers some areas of the process. These areas can, for example be subprocesses or relations between processes. The target process is then modeled as the process should be implemented to reach the objectives of the development project. (Martinsuo & Blomqvist 2010 p. 7)

When the target process has been modeled, the process should be piloted in simulated or real-life circumstances. The implementation of the process should be supported and followed in order to make changes to the process. Piloting is particularly useful if the consequences in real life setting can be severe. The piloting phase brings out important information on whether the wanted effects can be achieved. (Martinsuo & Blomqvist 2010 p. 7)

If development from the original process is seen in the piloting phase, implementation of the new process can be started. Implementation means that the old course of action, which includes for example instructions and routines, is replaced to match the new process. All the personnel taking part in the process are trained to implement the new process and the measurement system is adjusted to the new process. It is essential that the company’s way of operation and management systems support the new process. When the process has been taken into use, the process must be observed closely, and the feedback should be utilized whenever possible. The feedback can, for example be used to identify new development areas in the process. (Martinsuo & Blomqvist 2010 p. 7)

2.1.1 Business Process Re-engineering

Business process re-engineering (BPR) is an approach to management of processes first introduced by Hammer (1990) and Davenport and Short (1990). The definition by Davenport and Short is that BPR is the “analysis and design of work flows and processes within and between organizations”. (O’Neill & Sohal 1999) Agarwal (2010 p. 43) defines BPR in two ways. The first is that “the BPR is all about searching new business process and implementing them to achieve breakthrough results”. The second one is “the fundamentals rethinking and radical design of business process to achieve dramatic improvements in performance, cost, quality, service and speed”. In literature, BPR is mainly divided into 3 different categories. These categories are process improvement, evolutionary BPR and revolutionary BPR. (Fasna & Gunatilake 2019) These categories are explained in table 1.

Table 1. *Different categories of BPR (adapting Fasna & Gunatilake 2019).*

Type of BPR	**Definition**	**Characteristics**
Process improvement	A methodology that has been created to assist an organization in business process development	Incremental and gradual approach, little risk, easy to manage, changes are slow, sustained efforts lead to great overall impact
Evolutionary BPR	Possibly radical business improvement through incremental steps, which are similar to process improvement	Incremental steps to reach a radical improvement, has an impact on the whole company instead of a few processes
Revolutionary BPR	A BPR approach, which includes a one-time major process innovation to achieve a radical business improvement	Radical approach, intense period of disruption to achieve an improvement, requires significant financial input and results in greater improvements

Agarwal (2010 p. 46) has listed 9 benefits, which the organizations seek with BPR. These are cost reductions, time and space reductions, work life improvement, quality improvement, profit increase, securing future survival, customer satisfaction, convenience improvement, market share increase and quality of business improvement. Zairi and Sinclair (1995 p. 25) have also performed a survey in order to analyze the benefits of BPR. They agree with Agarwal on the listed ones and add process focus, organizational flexibility and employee development.

The presented tools and techniques used in BRP differ between publications. However, the core idea is the same. The tools include process visualization, process mapping/operational method study, change management, benchmarking and process and customer focus. (O'Neill & Sohal 1999) Fasna and Gunatilake (2019) have created a refined BPR implementation process. The implementation process is presented in figure 3.

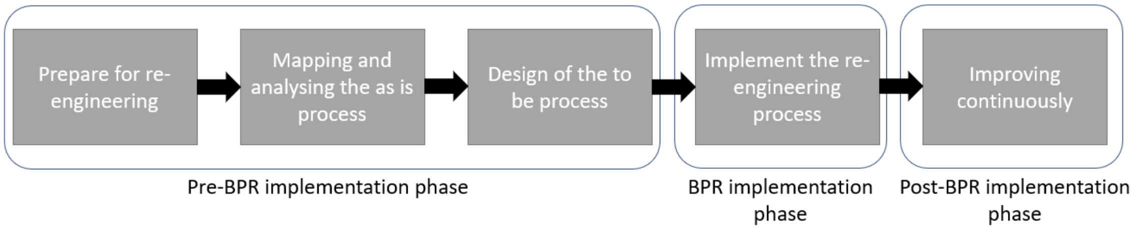


Figure 3. *BPR implementation process (adapting Fasna and Gunatilake (2019).*

As seen in the figure 3, the process can be divided into 5 steps and 3 phases. For these steps, Fasna and Gunatilake (2019) also present tools, which can be used to achieve the objectives set for the steps. However, most of these tools are quite case specific. Limam Mansar and Rejlers (2007 p. 198-199) have listed 29 of the most used practices in BPR. According to their survey study, the top 5 most used practices of BPR are task elimination, integral business technology, task composition, parallelism and specialist-generalist.

2.1.2 Process Mapping

Briefly, process mapping is done to add knowledge of the process. This added knowledge is then used to achieve a wanted goal. More specific reasons for process mapping can be, for example, helping to explain how something works, ensuring quality or willingness to improve the process with a new software. (Damelio 2012 p. 31-33) Aguilar-Savén (2004) agrees that processes are usually mapped in order to develop the processes or to develop an IT system which supports the operation of the process.

Martinsuo and Blomqvist (2010 p. 12-14) divide process mapping into two levels. The first level is a general description of the process. The general description concentrates on the core processes in question. In the general description, inputs, outputs, interfaces and the resources are defined on a general level. The second level is a detailed description of a process. This is recommended for processes, which are more critical for survival or efficiency. It is also recommended to create a detailed description when the process is carried out in the same way each time. (Martinsuo and Blomqvist 2010 p. 12-14)

In literature, several detail description process mapping techniques and charts are utilized. Aguilar-Savén (2004) presents two common techniques for process mapping: a flow chart and a data flow diagram. The flow chart can, for example be used to represent a logic sequence of a program, a manufacturing process or an organization chart. The chart is easy to use, and it is very flexible. However, with flow chart, mapping responsibilities or performers is complicated, and the chart can become large when mapping extensive or more detailed processes. Therefore, the flow chart is recommended as the process mapping technique when the process is simple or when the process map requires a high-level of detail. (Aguilar-Savén 2004) A visualization of a simple flow chart is shown in figure 4.

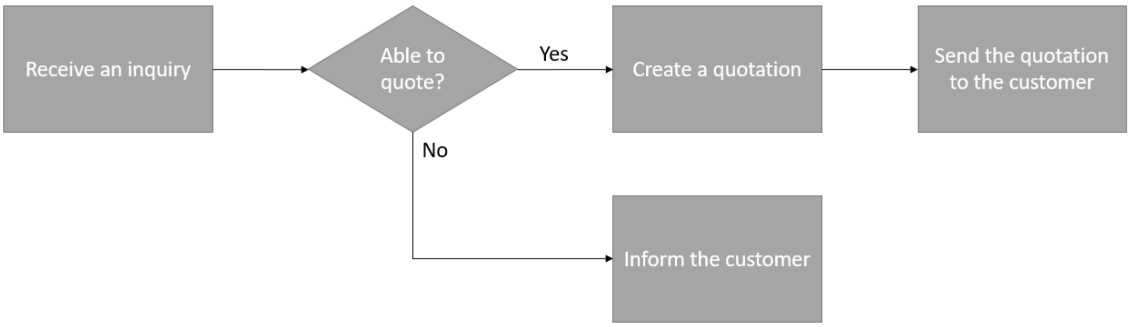


Figure 4. *Example of a simple flow chart process.*

The data flow diagram (DFD) is used to visualize the flow of data or information. The DFD can be used to show how the processes are linked data-wise. The DFD aims to visualize processes from the logical level instead of illustrating how the process is done. Use of the DFD is beneficial when recording the process analyses as a part of design documentation. The benefits of a DFD is that it is easy to understand and create. As the DFD only visualizes the data flow, in a process map where material flow is also required, DFD is not the optimal technique. (Aguilar-Savén 2004) A visualization of a simple data flow chart is shown in figure 5.

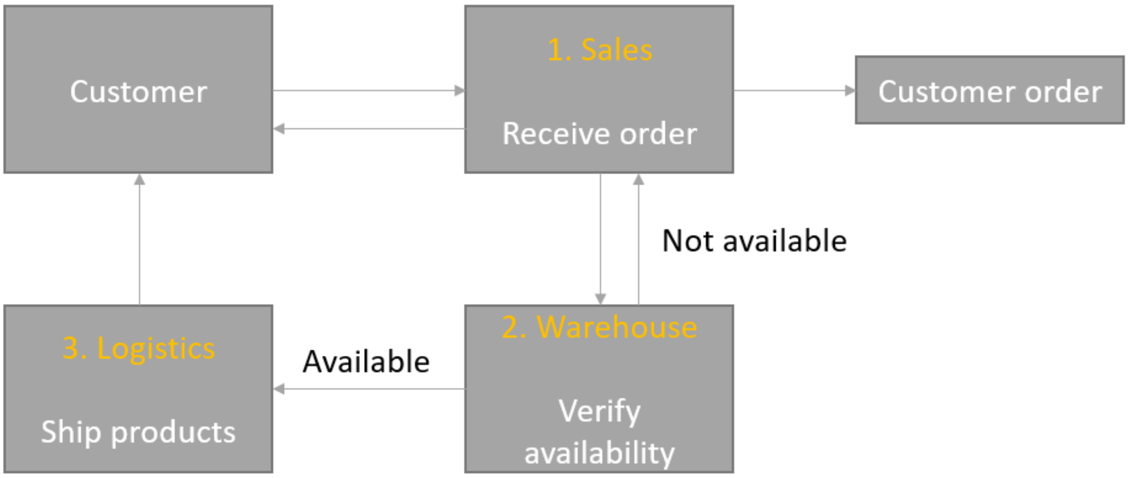


Figure 5. *Example of a simple data flow chart (adapting Aguilar-Savén 2004).*

Damelio (2012) also presents another way to map processes. A swimlane diagram visualizes the workflow between different organizational parts. These can be, for example, different departments. The workflow is a set of non-related activities or resources, also known as inputs, that follow a path and create and deliver value for the customer through outputs. In a swimlane diagram, visualization of activities is performed in different parts of organization is possible. (Damelio 2012 p. 6) A visualization of a simple swimlane diagram is shown in figure 6.

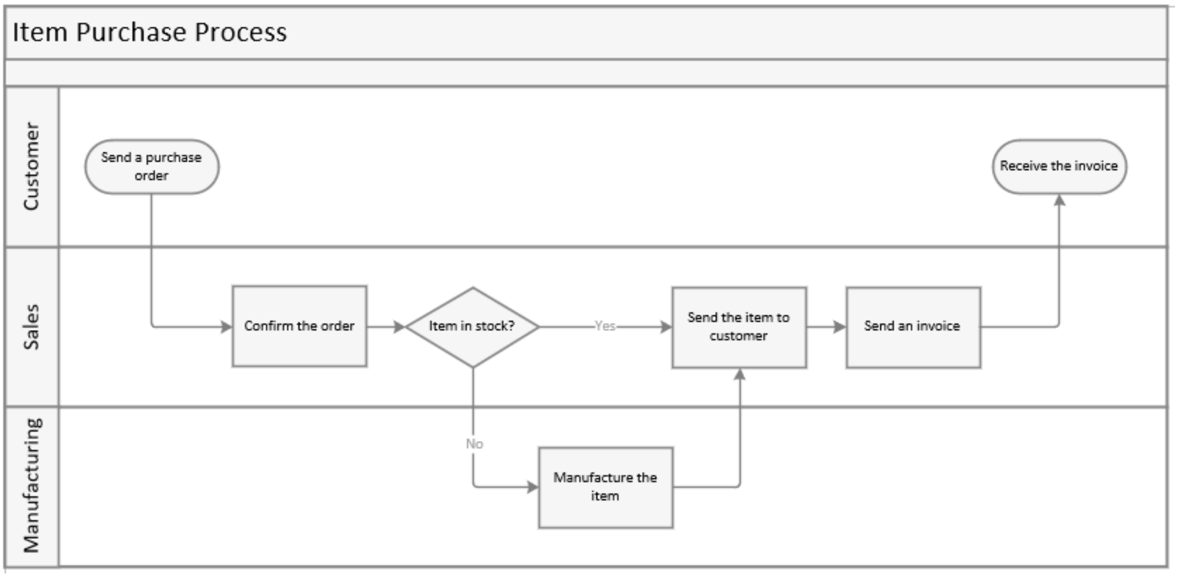
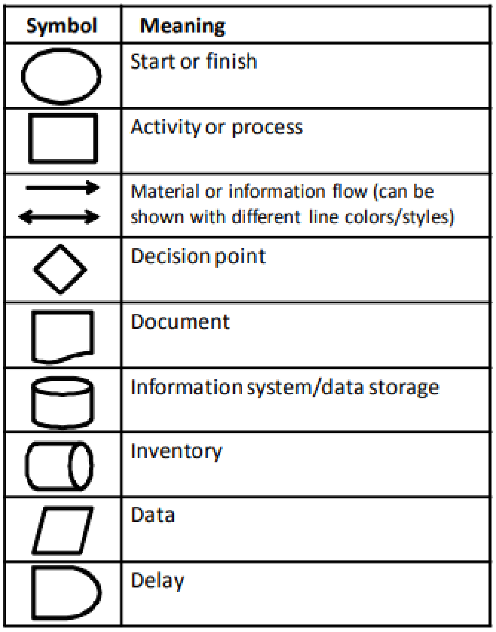


Figure 6. *Example of a simple swimlane diagram.*

Martinsuo and Blomqvist (2010 p. 15) provide the general key symbols that can be utilized in process mapping. Symbols that are used in the detail process mapping are not standardized and they can differ between publications. Symbols can also be company specific. These key symbols are shown in figure 7.



Symbol	Meaning
	Start or finish
	Activity or process
	Material or information flow (can be shown with different line colors/styles)
	Decision point
	Document
	Information system/data storage
	Inventory
	Data
	Delay

Figure 7. *Key symbols of process mapping. (Martinsuo & Blomqvist 2010 p. 15)*

The typical way to map a process is starting from the beginning to the end. This way it is easier to determine all the work and data required to create the final output of the process. While creating the detail description, it is also beneficial to determine which tools and systems are used in each task. (Martinsuo & Blomqvist 2010 p. 15)

2.1.3 Lead Time as a Process Performance Indicator

Performance indicator (PI) is a non-financial indicator that can be traced to a certain team. These indicators are used by teams to align their operations with organization's strategy. PIs are measured and reviewed frequently, for example, daily, weekly or monthly. PIs focus on a specific activity and all staff understand the activities required to improve performance. (Parmenter 2020)

Lead time is the time required to execute a process from start to finish. Lead time can be related to Lean ideology. The objectives of Lean is removing all possible non-value adding operations from the process. According to Lean, lead time can be reduced, in brief, by analyzing and mapping the current process thoroughly, applying Lean tools and implementing Lean. (Bradley 2015 p. 2) According to Little (1961) lead time can be calculated with formula:

$$Lead\ time = \frac{Work\ in\ progress}{Output}.$$

Therefore, if the output stays the same, lead time can be improved by decreasing the work in progress (Koskela 2000 p. 60). Koskela (2000) states that reduction of lead time does not only remove waste, but also enables faster deliveries to customers, reduces needs to make forecasts about future demand, decreases disruptions and eases management due to less orders to keep track of. According to Parmenter (2020) efforts to reduce lead time improve business performance, for example, by reducing inventory value, less rework and improved quality.

After the process has been mapped, the lead times, value-adding times and ratios have been analyzed thoroughly, opportunities to reduce lead time can be brainstormed (Bradley 2015 p. 69). Bradley (2015) has listed 8 tactics of Lean, which can be utilized to eliminate waste and thus the lead time of the process. These are

1. Simplify
2. Streamline
3. Standardize
4. Use visual systems
5. Mistake-proof process and product design
6. Synchronize
7. Collocate
8. Reduce changeover time

By using these tactics, development in lead time can be achieved. Within all of these tactics, several tools can be used to improve processes. (Bradley 2015 p. 69-70)

2.2 Design Automation

In this section the used keywords to find the references were “design”, “automat*”, “design automat*” and “design automation system”. These keywords were combined in different ways with the Boolean operators to find appropriate results. The main search engine in this section was also Andor. However, Scopus, SpringerLink and IEEE were also used to search more references. The used keywords were also searched in Finnish in order to find more references. The results were filtered to be preferably peer reviewed articles, books, theses and journals from 2015 to 2020. The selection was done by going through the titles, abstracts and table of contents and choosing appropriate publications. On this topic, also other publications on design automation were utilized to find more references.

Several definitions for design can be found from literature. Benavides (2012 p. 1) defines that “design is the result of consuming resources in order to provide a response to a motivation”. According to Sunnersjö (2016 p. 1), “engineering design is about planning products that are manufactured by an industrial process". Blessing and Chakrabarti (2009 p. 1) offer a much wider view that design is "activities that actually generate and develop product from a need, product idea or technology to the full documentation needed to realise the product and to fulfill the perceived needs of the user and other stakeholders". All these definitions share a similar core idea that design results in a product and activities are performed in order to create the product. Simulating this design process of design automatically is often referred to as design automation.

2.2.1 Benefits and Use of Design Automation

Design automation includes idealizing, modelling and simulating an original design process. When a new product is required, specifications are input in a computer model and the model is executed. This process results in an adapted product variant as an output. This computer model can be considered as a simulation on what the designer does during the design process. (Sunnersjö 2016 p. 4-5) A visualization of differences in a manual and an automated design process is shown in figure 8.

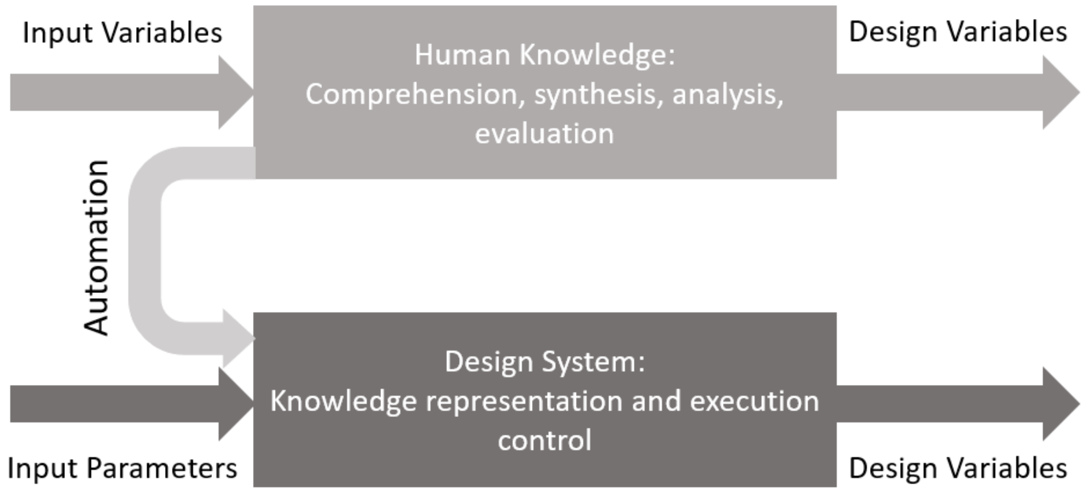


Figure 8. *Manual vs. automated design (adapting Sunnersjö 2016 p. 5).*

Reasons for design automation differ for different companies. The benefits gained from design automation can be assuring quality, minimizing lead times, optimizing design and removing routine work of designers for more creative tasks. Developing a large design automation system is a considerable investment in time and money, but once the implementation is completed, it is a crucial factor in the business of a company or an operation. (Sunnersjö 2016 p. 3)

According to Sunnersjö (2016 p. 19-20), the potential of design automation is the highest for technologically mature products that are produced in many variants. He has categorized design tasks suitable for design automation according to the degree of creativity. The list is in an ascending order of demands of creativity. These categories are:

- **Selection**: Individual component choices that are selected to satisfy certain customer needs.
- **Parametric design**: A design that is based on a basic design which adapts to input specifications, formulas, methods, constraints or relations.
- **Configuration**: Choice of individual components to be assembled into a system that satisfies customer needs.
- **Configuration of parametric components**: A combination of parametric design and configuration.
- **Redesign**: Adapting, modifying, improving and optimizing existing design solutions to fulfill new requirements.
- **Original design**: Design tasks are defined by requirement specification and given constraints, but the principles and the details are left to the designer.

2.2.2 Design Automation System Creation

Sunnersjö (2016) has divided systematic planning of a design automation system project into seven steps. These steps are 1) get acceptance and involvement, 2) define and delimit the problem, 3) evaluate cost/benefit, 4) acquire design knowledge, 5) clarify and map design process, 6) classify the problem and select the solution strategy and 7) select software and create a plan for implementation, maintenance and expansion. An illustration of the planning process is shown in figure 9.

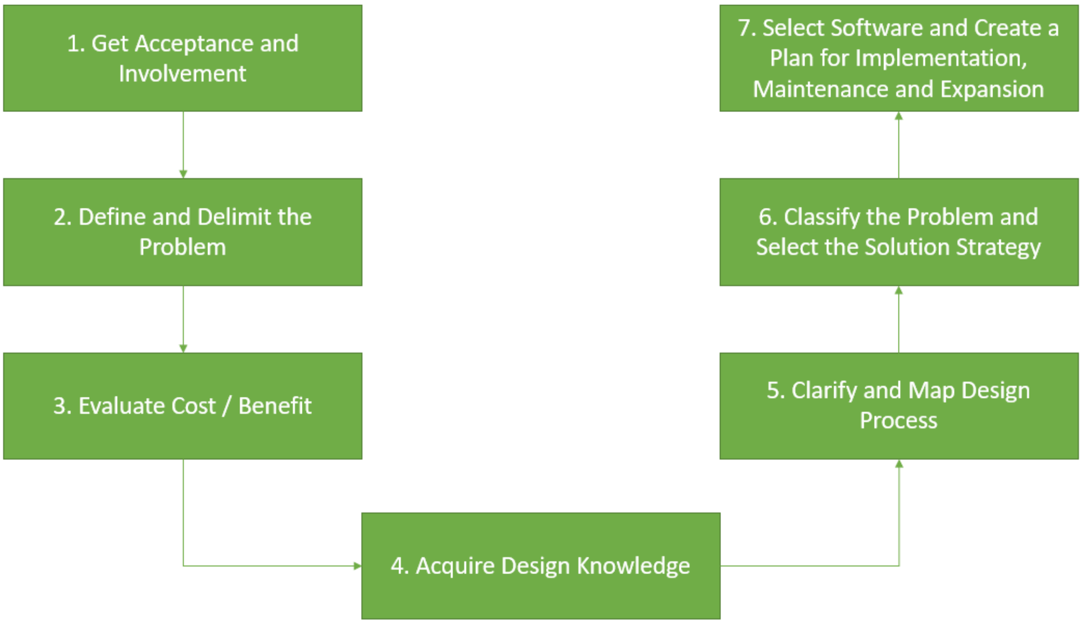


Figure 9. *Steps of planning a design automation system (adapting Sunnersjö 2016).*

Reliability and functionality of the design automation system heavily depends on the success of steps 4 to 5. The real challenge is changing design knowledge into programmable facts, rules and methods. (Sunnersjö 2016 p. 49)

After the planning phase, to assist with the actual system creation, Hvam et al. (2008, p. 44-45) have defined a normal project life cycle for creation of an IT system. The procedure consists of a cycle of four phases. The first phase is the analysis. During this step, a problem analysis and a requirement specification are done. The second step is the design. The design phase consists of creation of a draft design, creation of a detailed design and a verification of the design. After the design is completed and verified, programming the system can be performed. When programming is completed, implementation begins. After the implementation, it is essential to ensure that the system can be continually maintained and developed. In detail, these steps can be shown as project IT system life cycle. (Hvam 2008, p. 44-45) A visualization of the cycle is shown in figure 10.

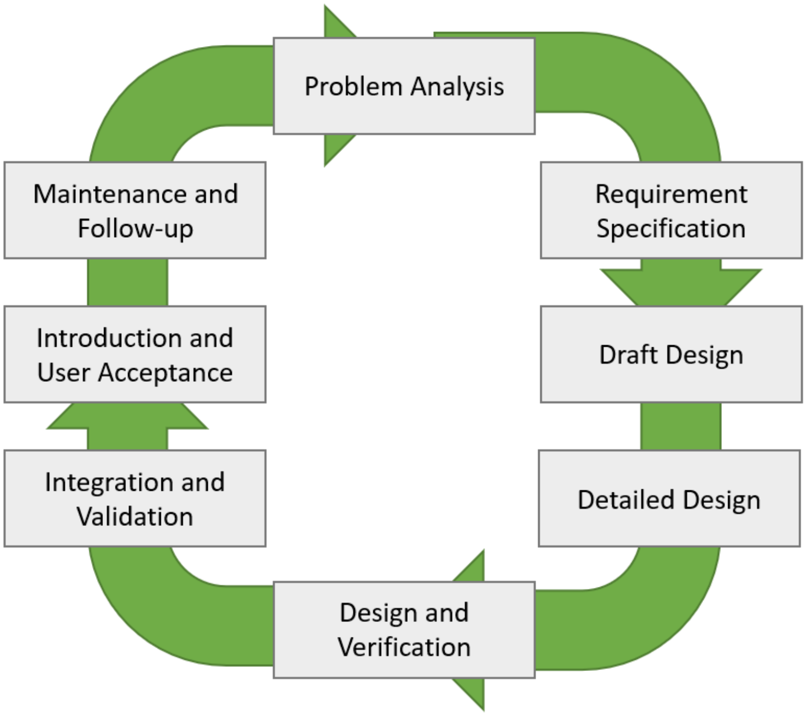


Figure 10. *Project life cycle during development of an IT system (adapting Hvam et al. 2008 p. 45).*

The creation of a design automation system should also be considered as a golden opportunity to review and streamline the design process in its entirety. The Lean thinking should be present in design automation system creation. For example, simplifying the design process and removing all useless documentation should be exploited whenever possible. (Sunnersjö 2016 p. 33)

3. RESEARCH METHODOLOGY

This research can, for the most part, be placed into the category of an evaluative design research. An evaluative study is a study, where the objective is to find out how well something performs. These kinds of studies are especially useful in business and managements studies when assessing the effectiveness of, for example an initiative or a process. (Saunders et al. 2019 p. 188). However, this study does have some characteristics of an exploratory study as well, mostly for chapters 2 and 4. An exploratory study is a valuable mean to gain insight and discover what is happening on a topic of interest. An exploratory study is useful when the researcher wishes to clarify their understanding of some topic. (Saunders et al. 2019 p. 186-187)

In this chapter, the research methodology is discussed and defined. Section 3.1 clarifies what is a design research. In addition, the section also presents a research rationale determination technique called research onion, which has been used to determine the research fundaments of the thesis. Section 3.2 presents the rationale behind the choices of research philosophy, approach and methodological choice. In section 3.3, possible research strategies are discussed, and the used strategy is chosen. Section 3.4 presents the chosen data collection and processing methods, of which the central core of the research onion consists.

3.1 Design Research

Blessing and Chakrabarti (2009), Frankel and Racine (2010) and Galle (2008) all agree that there is no common view to what a design research investigates, what are the objectives of a design research and how a design research is carried out. Most of the definitions mention the objective to improve the design in practice, rather than aiming to understand the design better (Blessing & Chakrabarti 2009 p. 4-5). Blessing and Chakrabarti (2009 p. 5) have defined that a design research has 2 main objectives. The first one is the formulation and validation of models and theories about the phenomenon of the design with all its facets. The second one is the development and validation of support founded on these models and theories in order to improve design practice. With "support" Blessing and Chakrabarti cover possible means, aids and measures that can be used to improve the design. This includes, for example, procedures, software tools and information sources. This study seeks to improve the process of pressure spare parts by experimenting and analyzing the potential benefits of design automation. As the products of interest are mature, development of the actual products is excluded from this thesis and the focus is on the design process.

Blessing and Chakrabarti (2009 p. 18) have divided researches into 7 types within the design research methodology framework. The division is based on whether the studies in each step are review-based, comprehensive or initial. For this research, the type can be considered as type 3. Type 3 means that a review-based research clarification is performed in the beginning of the study. In the research clarification phase, literature is reviewed in order to formulate the objectives for the study. After the research clarification, a review-based descriptive study I is conducted. In the first descriptive study, the objective is to create a description that is detailed enough to understand which factors improve the task clarification in the best manner. In addition to the descriptive study, a comprehensive prescriptive study is performed. The objective of the prescriptive study is to create the support based on the increased understanding gathered during the earlier phases. Finally, an initial descriptive study II is performed. In the second descriptive study, the impact of the support is evaluated. (Blessing and Chakrabarti 2009 p. 15-17) As the time period in this study was limited, no proper iterations were performed between these phases during the research process.

Saunders et al. (2019 p. 128-130) have created a diagram called the “research onion” to visualize the rationale behind the choice of data collection and analyzing methods. The idea of the research onion is that you must go through the research choices in the outer layers before you can make the decision of the central core, visualized as the data collection and processing methods. A visualization of the rationale following the research onion is shown in figure 11.

Research Philosophy: **Pragmatism**

Research Approach: **Induction**

Methodological choice: **Mixed Methods Study**

Research Strategy: **Case Study**

Time Horizon: **Cross-Sectional**

Data Collection and Processing Methods:
Literature Review
In-depth Interviews
Existing Materials
Process Mapping
Process Piloting

Figure 11. *Research rationale of the thesis.*

During the process of determining the rationale, different options were considered. However, the rationale presented in figure 11 was presumed be functional in this type of research.

3.2 Research Philosophy, Approach and Methodological Choice

All the research choices are based on the research philosophy. Understanding the research philosophy is an essential part in making research (University of Jyväskylä 2015b). In this research, the philosophy behind the choices was closest to pragmatism. Pragmatism is a philosophy that underlines the practical characteristics of information. The philosophy includes a variety of orientations that connect emphasizing action and practical orientation in research, problem solving and producing information. (University of Jyväskylä 2015a) In a research driven by pragmatism, the research begins with a problem and the objective is to find practical solutions that inform the future practices. (Saunders et al. 2019 p. 151)

Research approach is divided in literature to deduction and induction. In most research, the actual research approach is a combination of both induction and deduction. (Saunders et al. 2019 p. 152-153) In this thesis, the emphasized research approach was induction since there was no hypothesis or theory to begin with and the role of the researcher was subjective. In addition, in the discussion part of the study, inductive reasoning on the results was performed.

The methodological choice in this thesis was mixed methods study. Mixed methods studies are studies, which utilize both qualitative and quantitative data collection and analysis methods. (Saunders et al. 2019 p. 181) All the data collection methods were qualitative. However, in the analysis part, data was analyzed both qualitatively and quantitatively.

3.3 Research Strategy

A research strategy can be defined as a plan how the researcher seeks to answer the research questions presented in section 1.2 of the research. Research strategy is the link between the research philosophy and the choice of methods to collect and analyze data in a research. (Saunders et al. 2019) The two possible research strategies for this thesis were action research and case study.

According to University of Jyväskylä (2015d), the objective of an action research is to develop or improve the surroundings, ways of operation or actual subjects of the research. The development or improvement is done by engaging the researcher in the operation of the research subject. Saunders et al. (2019) describe action research as an iterative process that consists of cycles of diagnosing, planning action, taking action and evaluating action. Action research has a longitudinal nature and therefore action research is suggested for medium- or long-term research processes (Saunders et al. 2019 p. 204). The time period of the research was fairly short and evaluating action takes a while in this kind of business. In addition, the research process required a deeper understanding of the product portfolio, process and design automation. Gaining this understanding would have taken a large proportion of the research time. Therefore, action research proved not to be a suitable research strategy in this research.

Yin (2018 p. 2-4) has stated that a case study is a viable strategy in researches, which seek to explain some contemporary circumstance. According to Yin, the case study method is preferred when the main research questions are either “how” or “why”. A case study is an in-depth study about a topic or phenomenon within its real-life setting. (Yin 2018). The case may refer for example to a person, an organization, or a change process (Saunders et al. 2019). Yin (2018) divides case studies into single and multiple case studies according to the amount of studied cases. Yin also divides case studies to holistic and embedded according to the units of analysis. According to Yin’s division, the case study in this thesis is an embedded single case study as there are several units of analysis, for example, the different organizational levels and different projects that are being analyzed inside the actual case.

University of Jyväskylä (2015c) states that a case study seeks to produce detailed information on the chosen case. When a deeper understanding of the case has been gained, interpretation of the phenomenon in a particular context is possible. The objective of a case study is understanding the dynamics, mechanics and internal processes of the phenomenon in a way that the results can be considered reliable within a broader context. (University of Jyväskylä 2015c)

The objective of this research was to gain a deep understanding of the use of design automation on a single product within the pressure spare part product portfolio. Therefore, the objectives were in line with the objectives of a case study. In addition, the main research question in this thesis was "how does creation of a design automation system affect the lead time of the pressure spare part process?". For these reasons, case study was considered as the best option as the research strategy for this research.

The case study in this thesis was creating a design automation system for tube bends, which are the simplest pressure spare parts, and analyzing the achieved lead time effects. The analysis was done by piloting the process, which was redefined to include the use of design automation and comparing the results to completed delivery projects. As a large amount of completed delivery projects had been documented during the past years, a comparison between the earlier projects and the achieved lead times could be performed. Creation of a single tube bend manufacturing drawing from scratch takes roughly a few hours. Other pressure spare parts are slightly more complicated, and the creation of the manufacturing drawings takes longer. Therefore, as the lead time analysis was performed on the simplest and least time-consuming pressure spare parts, the potential lead time effects of design automation could be inductively evaluated on the more complicated spare parts.

3.4 Data Collection and Processing Methods

In this thesis, 5 different qualitative data collection methods were used. The first utilized data collection method in this thesis was the literature review. Literature was used to deepen the understanding process development, design automation and water-tube boilers. In addition, the literature was used to compare the achieved results and benefits of the process re-engineering to other similar processes. In the case study, literature, more specifically the standards, that were related to the design and manufacturing of water-tube boiler pressure parts were reviewed in order to find the means to fulfill the requirements set by PED 2014/68/EU. When the means were clarified, the actual design automation system could be created. A brief summary of how the references were found, was also included on each literature review topic. This summary included the databases, keywords and filters used in the search process.

In the design automation system creation phase, to help with the process and design requirements identification, in-depth interviews were utilized. In-depth interviews are unstructured interviews that do not use a predetermined structure to guide the interview (Saunders et al. 2019 p. 438-439). The interviews were conducted in the same group, which consisted of the researcher and the 2 supervisors from the company. Other supervisor was working as a Chief Engineer in the energy service department and the other one was working as an Operations Development Specialist in the energy spare part department. Both supervisors had worked for the company for several years and had gained knowledge of the processes in question. Therefore, they were able to confirm and correct the observations by the researcher.

The third data collection method was existing materials. The materials consisted of internal documents, such as drawings, process descriptions and delivery project documents. These materials were observed to gain a better understanding on what must be considered when mapping the process, analyzing the current lead times and creating the design automation system. In the existing material collection phase, the objective was to analyze various projects in order to equalize the effects of project variation. This method was selected since it provided a lot of valuable information of the previously completed projects. As they were already completed, all the required information had been recorded to the project documentation. Therefore, the comparison was easy and reliable.

The data was also collected and analyzed qualitatively by mapping the current pressure spare part process and the process after implementing the design automation system. The objective of the process mapping was to visualize all the activities, data, IT systems and departments included in the process. Process mapping was also a part of the BRP, process development, Lean and design automation system creation processes. Therefore, it was chosen as a data collection and processing method in this research.

After the process redefinition process, the process was piloted in simulated circumstances. During the piloting phase, data was collected in order to compare the achieved results to existing project data. In this phase, the projects were selected randomly to increase the reliability of the results. The selection process was performed by examining whether the manufacturing drawing could be created with the design automation system. Therefore, the lead time data of the project was not known to the researcher prior to the choice of including them in the piloting process. After the process had been piloted, the results were then compared quantitatively to the data acquired from the old projects.

4. WATER-TUBE BOILERS

This chapter presents the basics of 3 different water-tube boilers and the fundaments behind the design and maintenance of boiler pressure parts. Understanding the operation of boilers is critical in understanding the complexity of the design automation system and the process behind the pressure spare parts. In section 4.1, different boiler types are introduced. This includes an explanation of the operational fundaments of each boiler. Section 4.2 presents the steam-water circulation, which is essential in understanding the pressure parts of the boiler. After the steam-water circulation, in section 4.3, the boiler pressure parts are introduced. The introduction includes the operation, typical issues and common spare parts of the pressure parts. Section 4.4 provides basics behind the legislation of boiler pressure parts. Basic understanding of the legislation is required in order to understand the pressure part design and delivery process better. Finally, in section 4.5, boiler maintenance and spare parts are discussed. This provides an understanding on how the maintenance and spare parts are handled in water-tube boiler business.

In order to find the references for this chapter, used keywords were “water-tube boiler”, “water tube boiler”, “biomass boiler”, “boiler”, “recovery boiler”, “bubbling fluidized bed boiler”, “circulating fluidized bed boiler”, “steam-water circulation”, “steam water circulation”, “pressure equipment”, “pressure part”, “spare part” and “maintenance”. The main search engine that was used to find references was Andor. Scopus database was also used to find more references. These keywords were combined in different ways in order to find relevant references for this chapter. The results were filtered to include preferably peer reviewed articles, conference papers, books, business articles and journals. In addition to the search results, references were also gathered from other publications on water-tube boilers. The selection was made based on the titles, abstracts and table of contents of the publications.

4.1 Boiler Types

The steam plants these days are complex engineered systems that are used to produce steam in an economically feasible and efficient way. In every situation, a steam power plant needs to obtain heat. This heat can be obtained from different sources, such as fossil fuels, nuclear fuels, or other forms of fuels, such as biomass or waste. The systems that are used for steam generation are called boilers, often also called steam generators. (Woodruff et al. 2017) Traditionally, a boiler is simply considered an enclosed container where combustion happens. This combustion generates heat that is then transferred into working media, usually water, until vaporization of the water. Vaporized water is then directed onwards. Therefore, a boiler can be simply described as a heat exchanger between fire and water. (Teir 2003 p. 4) Boilers can be classified in three different ways: by their combustion method, application or type of steam-water circulation (Teir 2003, p. 33). Due to the thesis definition, in this thesis the focus will be in 3 water-tube boilers: recovery, bubbling fluidized bed and circulating fluidized bed boilers. In brief, a water-tube boiler is a boiler, where the end products of combustion (called flue gases) pass around tubes containing water (Woodruff et al. 2017). The steam-water circulation of the boilers is explained in detail in section 4.2.

4.1.1 Recovery Boiler

In a pulp mill a recovery boiler is used mainly for five different functions. The first function is burning the organic materials of black liquor created during cooking of pulp to generate steam. In recovery boilers, only black liquor can be burnt. The high-pressure steam is then used for generating electricity. Recovery boiler is normally the main energy producer of a pulp mill (80 – 100 %). Generated energy can also exceed the energy consumption of a pulp mill and the excess energy can then be sold to external customers. Second function is reducing inorganic sulfur compound to sodium sulfide (Na_2S). Third function is the production and dissolution of smelt, which consists mainly of sodium carbonate and sodium sulfate, to produce green liquor. Fourth function is the recovery of inorganic dust to save chemicals from the flue gas. Fifth function is the production of sodium fume to capture combustion residue of released sulfur compounds. (Vakkilainen 2005, p. 1; Vakkilainen 2017, p. 239-240; Valmet Technologies 2018). An example of a recovery boiler arrangement and the location of recovery boiler pressure parts is shown in figure 12. The figure illustrates Valmet’s recovery boiler.

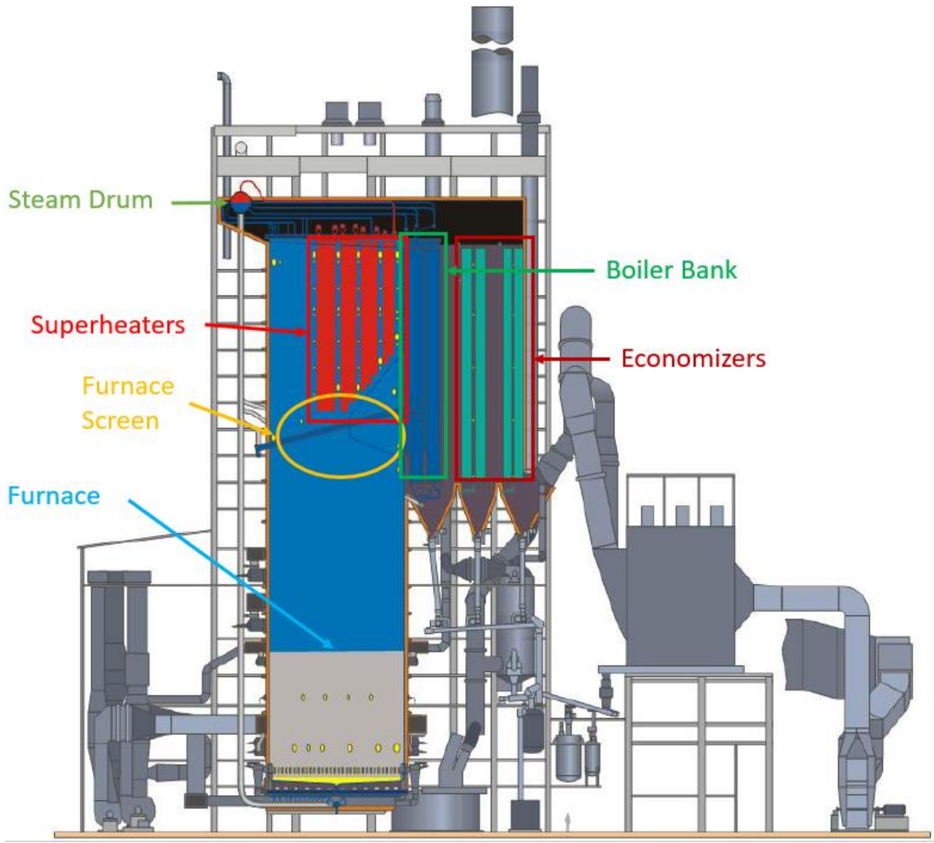


Figure 12. *Recovery boiler arrangement (Välimäki et al. 2010).*

The pressure parts in this arrangement are shown in the figure. The operation of these pressure parts will be explained more thoroughly in section 4.3.

4.1.2 Fluidized Bed Boilers

Fluidized bed boilers can be used for energy and heat generation. A large variety of fuels, for example, coal, peat and wood chips can be burnt in fluidized bed boilers. The operation principle of fluidized bed boiler is creating a solid-state reactor that operates like a liquid phase reactor. If a layer of sand is placed in a furnace and high-pressure air is blown through large number of nozzles from below, the particles become entrained in the air and form a fluidized bed of solid particles. This way the solid particles behave like the molecules in a liquid. Fluidized bed boiler offers an advantage since the reactions between the particles within the bed are more rapid and thorough. A fluidized bed used for power generation uses only around 5 % of fuel within the actual bed. Rest of the bed is primarily inert material, such as sand or ash. Fluidized bed boilers have begun to dominate the markets over grate-fired boilers for boilers sized over 10 MWth. The two main types of fluidized bed combustion are BFB and CFB boilers. (Breeze 2019; Rosendahl 2013; Vakkilainen 2017, p. 211-212)

Bubbling fluidized bed boiler is the simplest fluidized bed boiler. The main difference to a conventional boiler is that the combustion chamber has been replaced with a fluidized bed. Air is blown from the bottom of the furnace with relatively low velocity to maintain a liquidlike bed. Fuel is added to the furnace from above the bed and ash is removed from below the bed. Additional air is blown above the bed to complete the combustion of the particles. The main advantage of a BFB boiler is the capability to burn more varieties of fuel than a normal coal boiler, therefore BFB boilers are often used in biomass plants. BFB boilers typically have a power output lower than 100 MW. In a coal burning BFB boiler, the combustion efficiency typically varies from 85 – 90 % due to the unburnt carbon. (Breeze 2019; Sarkar 2015; Teir 2003, p. 38-39) An example of a BFB boiler arrangement and the location of BFB pressure parts can be seen in figure 13. The figure illustrates Valmet's BFB boiler.

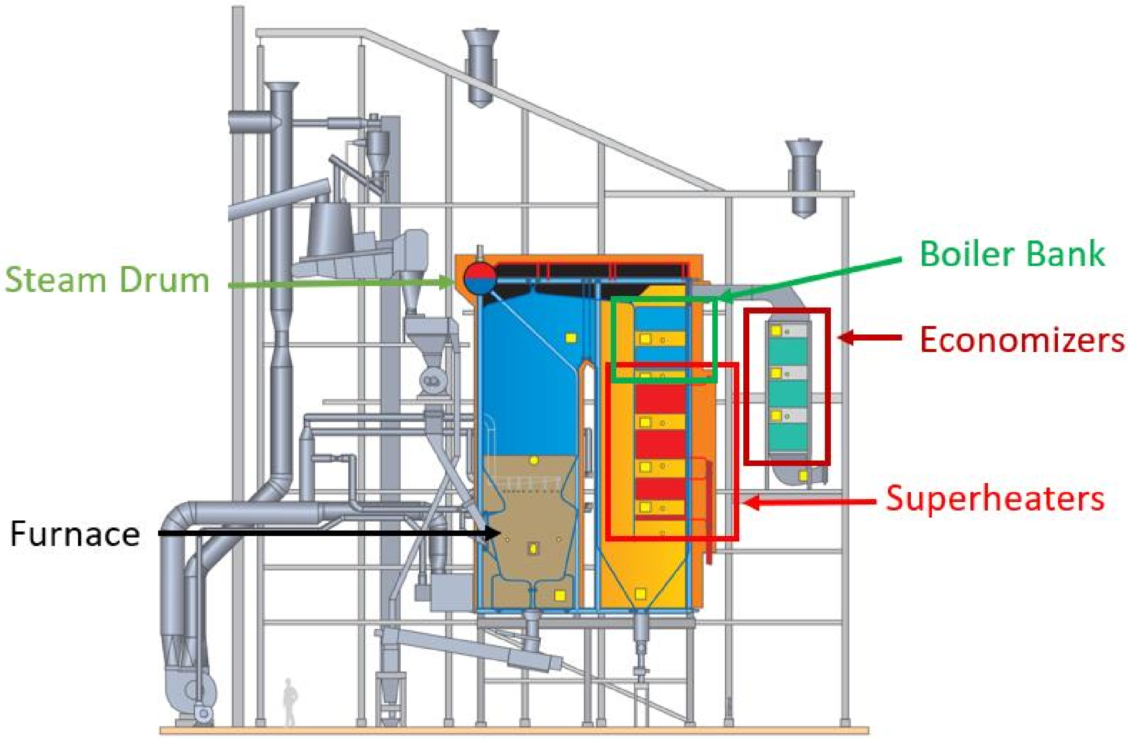


Figure 13. *BFB Boiler arrangement (Valmet Oyj 2020b).*

Pressure parts of this BFB arrangement are also shown in the figure. The operation of these pressure parts will be explained more thoroughly in section 4.3.

Circulating fluidized bed boiler is a more complex version of a fluidized bed boiler. In CFB boilers the particles are fluidized at high speed by using high velocity air in order to create a fluidized cycling mass. The particles pass up out of the furnace and are then recirculated. Flue gas flow is directed through a cyclone filter, where particles are directed back to the bed while flue gases flow onwards. CFB boilers are mainly used for power output range from 100 MW to 500 MW. CFB boilers are installed mainly because of the need for higher efficiency and pro-environmental boilers. CFB boilers have an advantage over BFB boiler due to its higher combustion efficiency, lower NOx emissions, quicker response to load changes and lower limestone consumption as a bed material. In a coal burning CFB boiler the combustion efficiency can be over 98 % due to the recycling of the solids. (Breeze 2019; Sarkar 2015; Teir 2003, p. 38-39) An example of a CFB boiler arrangement and the location of CFB boiler pressure parts is shown in figure 14. The figure illustrates Valmet's CFB boiler.

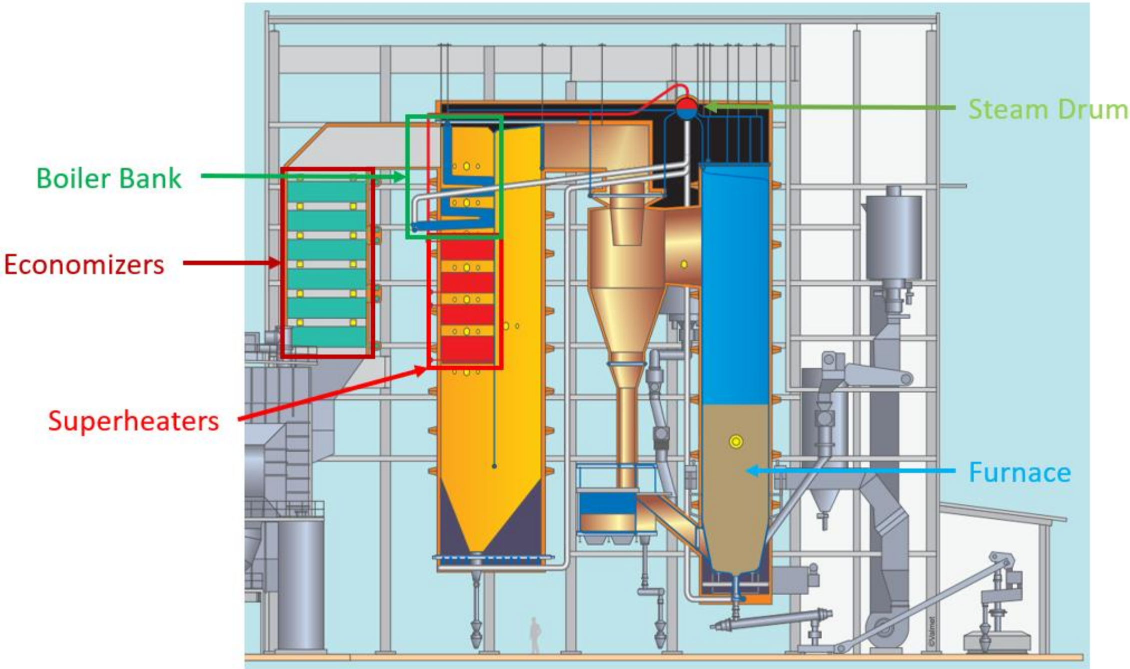


Figure 14. *CFB Boiler arrangement (Valmet Oyj 2020b).*

The pressure parts of this arrangement of CFB are shown in the figure. The operation of these pressure parts will be explained more in detail in section 4.3.

4.2 Steam-Water Circulation

The components receiving heat in these boilers form the so-called steam-water system. Objective of these components is simply turning water to steam. Water tube boiler water-steam circulation can be classified into 4 different types according to the arrangement of the steam-water circulation. These 4 types are natural circulation, forced/assisted circulation, once-through and combined circulation. As next to all the focused boilers are natural circulation boilers, only natural circulation will be discussed in this thesis. This type of circulation is called "natural" because there are no pumps to force the circulation and the circulation happens by itself due to the density difference between downcomers and wall tubes (Teir 2003, p. 54-55; Vakkilainen 2017 p. 74).

In the natural circulation, feedwater is pumped from a feedwater tank into the steam-water system. As soon as the feedwater enters the boiler from the tank, it is heated in the economizers and then directed into the steam drum, where steam and water are separated. Saturated water flows downwards in downcomers, which are the tubes leading from the steam drum to the bottom of the boiler. A small amount of saturated water, called blowdown, is used to purge impurities from the boiler water. The separated steam from steam drum is led to the superheater tubes, where it is then heated beyond the saturation point. After the steam has reached its saturation point, the steam exits the boiler. (Teir 2003, p. 55; Vakkilainen 2017, p. 74) Operation principle of a simplified natural circulation is shown in figure 15.

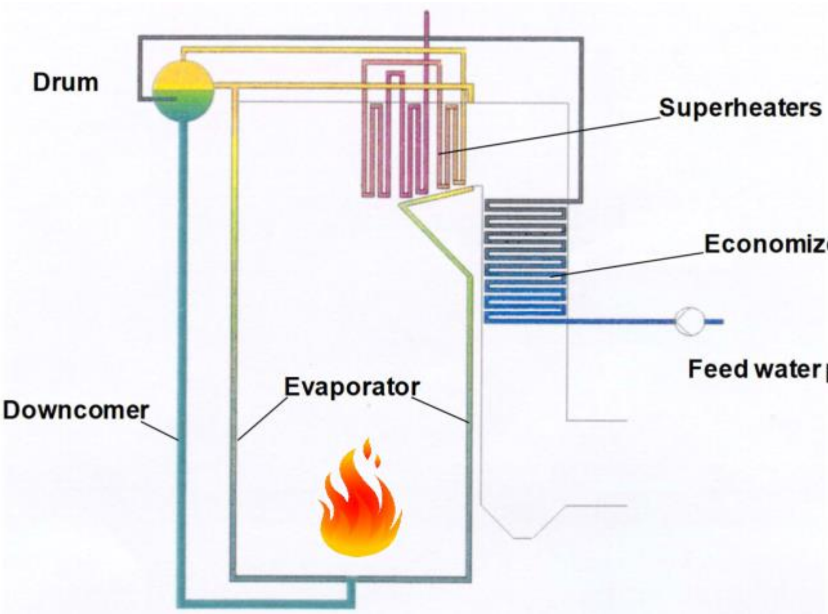


Figure 15. *Natural circulation arrangement (Valmet Technologies 2018).*

The evaporators in the figure are the furnace wall tubes. The operation of these steam-water components, presented in the figure, is explained more thoroughly in section 4.3.

4.3 Boiler Pressure Parts

The pressure equipment of a boiler are in literature often referred to as boiler pressure parts. The European pressure equipment directive considers pressure equipment as all stationary pressure equipment with a maximum allowable pressure greater than 0.5 bar (European Commission 2016). As shown in figures 12, 13 and 14, the main pressure parts of the introduced boilers are furnace, steam drum, boiler bank, superheaters and economizers.

4.3.1 Furnace

Furnace is the location in boilers where the fuel is burnt. The target is to burn the fuel completely and as stably as possible. The unburnt fuel decreases the efficiency and increases the emissions of the boiler. Objective for the equipment manufacturer is making the furnace as reliable and cost-efficient as possible. The furnace wall tubes work as the evaporators of the water-tube boilers. Water is led into the furnace wall tubes through the downcomers and the steam generated by the combustion heat is then directed into the steam drum. The furnace walls are typically built as a gas-tight membrane wall. The membrane consists of tubes welded together with flat iron strips, called fins or membranes. (Teir 2003, p. 106; Vakkilainen 2017, p. 116-117) A visualization of the membrane wall structure can be seen in figure 16.

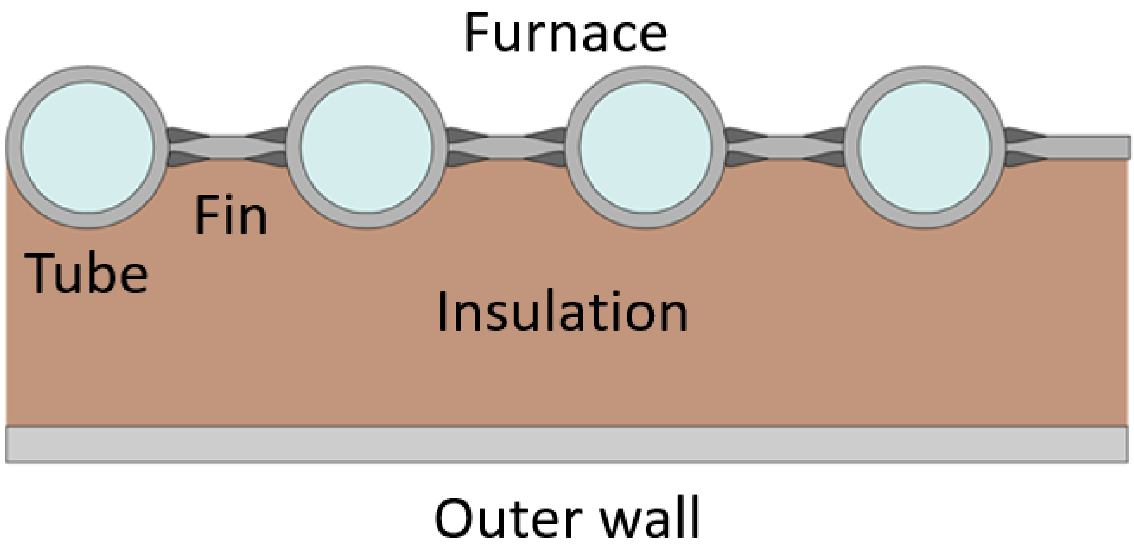


Figure 16. *The membrane wall structure (adapting Teir 2003, p. 106)*

As the combustion causes high temperatures, reactive gases and molten ash, material selection is essential in the design process of the furnace walls. A combination of high-temperatures, ash deposits and reactive gases causes high-temperature corrosion. High-temperature corrosion, in brief, is the destruction of the normal tube surface due to high temperatures. Furnace is one of the most problematic areas with high-temperature corrosion. This corrosion can be handled by applying a protective layer over the panels. Overlay welded tubes and composite tubes are the appropriate protection against corrosion. (Vakkilainen 2017 p. 184-191) Erosion also causes wear especially in the lower furnace. In brief, erosion is the wear which happens when a particle hits a surface and removes material. The erosion rate increases as the velocity of the particles increases. Erosion can also be controlled by applying a protective layer, which is harder than the protected material. Refractory is an appropriate protective layer against erosion. (Vakkilainen 2017 p. 184-191) Unequal distribution of combustion and overheating can also result in unequal wear of the membrane wall. This wear can be reduced and prevented by correct operation and maintenance of the combustion equipment. (Woodruff et al. 2017) This maintenance includes changing the worn areas of the furnace wall. These pressure spare parts are often referred to as wall panels. Wall panels can be, for example, 8 fixed length tubes with fins welded between them. The furnace bottom can, in some boilers, be built partly using the membrane structure, so the floor panels can be like the wall panels. A replaced floor panel, which is like wall panels, can be seen in figure 17.

Figure 17. *Replaced floor panel. (Valmet Technologies Oy 2017)*

In the furnace walls, there are several wall openings for different auxiliary equipment. The openings are made, for example for burners, access doors and fuel feeding. The openings are made from bended tubes, straight tubes and fins. Openings differ from manufacturer to another due to the difference in design of auxiliary equipment. Smaller wall openings are also common pressure spare parts in the furnace area. Wall panels and wall openings can be replaced by cutting the tubes and fins and replacing them with a new wall panel or wall opening. A wall opening is shown in figure 18.

Figure 18. *Wall opening of a BFB boiler. (Valmet Technologies Oy 2017)*

In some boilers additional evaporator tubes are required to reach the wanted evaporation. In these boilers, a boiler bank can be used to increase the evaporation area. A boiler bank is normally used parallel with a natural circulation-based furnace. Boiler banks have become less popular and they are only used in boilers with low pressures and small boilers (Teir 2003, p. 106) Examples of the design of a boiler bank can be seen in figures 12, 13 and 14. Typical pressure spare parts in boiler banks are tube bends and straight tube.

4.3.2 Steam Drum

Steam drum is a key component in natural circulation boilers. The functions of a steam drum are mixing feedwater with circulating boiler water, supplying circulation water to the evaporator through the downcomers, receiving water and steam from the wall tubes, separating steam and water, removing impurities, controlling the chemical balance by chemical feed and blowdown, supplying saturated steam to steam-water system, storing small amounts of water and acting as a reference point for feedwater control. Water and steam are led in different directions from the steam drum. Water is directed from the bottom to the downcomers and steam is directed from the top to the superheaters. The steam drum is placed in the highest possible point to maximize the height difference between the steam drum and the height where evaporation begins inside the furnace wall tubes. (Teir 2003, p. 73-74) An example of a steam drum cross-section cut is shown in figure 19. On the left side of the figure, NWL is the normal water level.

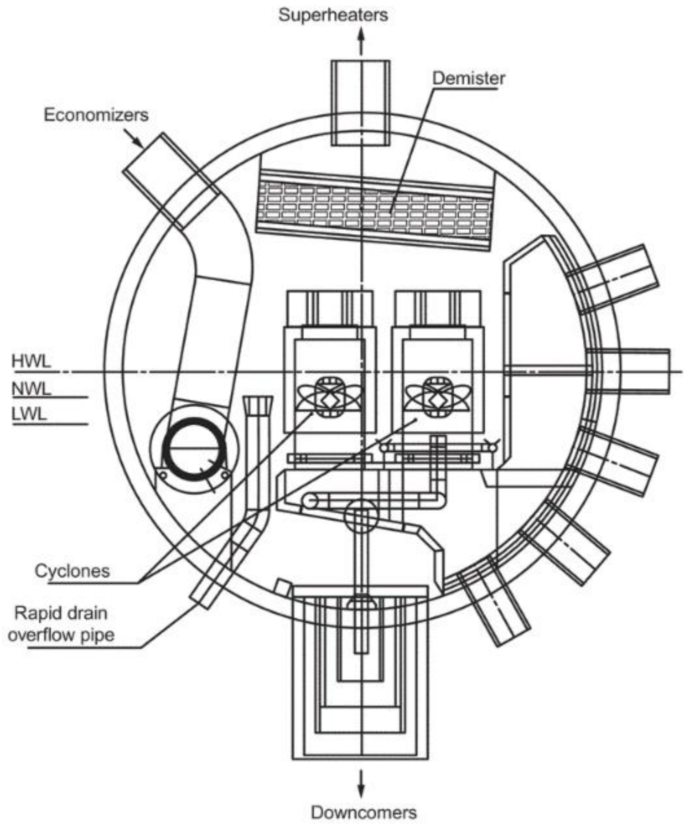


Figure 19. *Cross section cut of a steam drum (Vakkilainen 2017 p. 101).*

The steam drum is made of bent steel plate with two forged ends. It can either be made of single thickness sheet in case the pressure inside the drum is low, or from thicker plates, if the pressure is higher. (Vakkilainen 2017 p. 101) The spare parts for steam drums are generally not pressure parts. Thus, the steam drum spare parts are not discussed in more detail.

4.3.3 Superheater

Superheater is a heat exchanger used for superheating the saturated steam from the steam drum. Superheating means that the steam is heated above the saturation temperature of the corresponding pressure. The superheated steam contains more heat than a saturated steam at the same pressure. Thus, more energy is gained when the steam is directed through the turbine after superheating. Superheaters can either be radiation-based or convection-based. The difference between them is that in radiation-based superheaters, the heat is mostly transferred with radiation and in convection-based superheater the heat is mainly transferred with convection. A radiation superheater is placed in the furnace, where it can receive most of its heat by radiation. A convection superheater is placed somewhere in the flue gas stream where it can receive the heat by convection. There are normally several units of superheaters in a single boiler. (Teir 2003, p. 107-108; Woodruff et al. 2017)

As the superheaters are placed in the flue gas stream, superheaters must be designed to handle high temperatures, loads of molten ash and reactive gases. Along with the furnace, superheater area is the other area where high-temperature corrosion has to be taken into account during the design process, especially in boilers with steam temperature over 450 °C. Superheater tube corrosion has been a barrier for achieving higher efficiency performance. Corrosion can however be handled by using better materials. (Keiser et al. 2009 p. 117; Vakkilainen 2017, p. 170-185) Typical pressure spare parts for superheaters are tube bends and straight tubes. A replaced superheater bend is shown in figure 20.

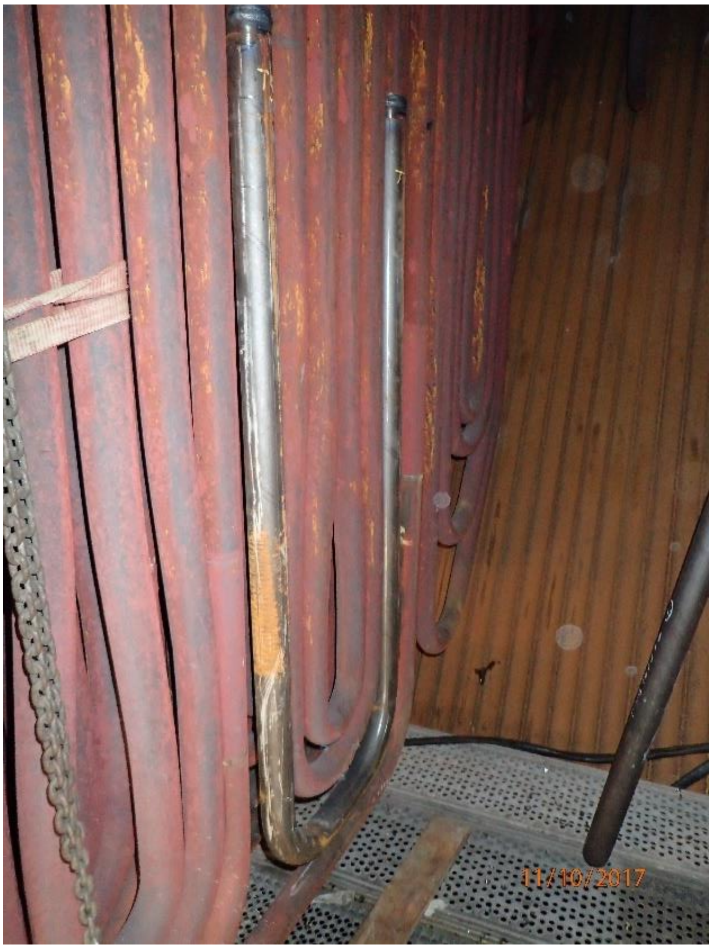


Figure 20. *Replaced superheater tube bend. (Valmet Technologies Oy 2017)*

Replacing the superheater bends is done by cutting the ends of the tube bend from a certain length and then welding a new bend to the existing superheater tube. The cutting length is defined by the installation availability.

4.3.4 Economizer

Economizer is placed as the last flue gas steam-water heat exchanger, usually in the form of tube packages. The objective of economizers is cooling the flue gases and preheating the feedwater from the feedwater tank. This temperature reduction of the flue gases increases the boiler heat efficiency. In an ideal situation, preheating would be done up to the saturation temperature. However, in reality, some margin for evaporative temperature is required in order to prevent boiling. Economizers are typically constructed as a package of tubes attached to the flue gas passage walls. (Teir 2003, p. 107; Vakkilainen 2005; Vakkilainen 2017, p. 171)

The material choice in economizers is not as crucial as the temperature of the flue gas has cooled down significantly when entering the economizer area. However, some low-temperature gas side corrosion does happen in the economizer area. Low-temperature corrosion is often associated with acidic deposit formation. (Vakkilainen 2017 p. 186-187) Typical pressure spare parts in the economizer area are straight tubes and tube bends.

4.4 Pressure Part Legislation

Design of all pressure equipment is strictly controlled by laws and standards. Different laws and standards are applied around the globe. Laws and standards follow the same core ideas but in some parts of the world the requirements, for example for inspections, are stricter. European Pressure Equipment Directive (2014/68/EU) is the directive followed in most parts of Europe. Thus, the focus of this thesis is on the requirements set by PED.

SFS-EN 12952 “Water-tube boilers and auxiliary installations” standard has been created by Finnish Standards Association SFS to provide means of conforming essential requirements set by the directive. Therefore, by following the standard, the requirements of the directive are met. The standard is applied to water-tube boilers that are built for steam and/or water generation with volume exceeding 2 l, maximum pressure exceeding 0.5 bar and temperature exceeding 110 °C. The standard also applies to other plant equipment. (SFS-EN 12952-1 2015, p. 5-14).

According to the regulations of CEN (French: Comité Européen de Normalisation, European Committee for Standardization) / CENELEC (French: Comité Européen de Normalisation Électrotechnique, European Committee for Electrotechnical Standardization), the standards organizations of the following countries are obliged to acknowledge the standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, the Netherlands and the United Kingdom. (SFS-EN 12952-1 p. 1)

4.5 Boiler Maintenance and Spare Parts

In brief, maintenance is a set of actions, which must be performed in order to ensure the functionality of a system. Maintenance can be divided into preventive maintenance and corrective maintenance. Preventive maintenance is the maintenance carried out at predetermined intervals to reduce the probability and interval of a failure. Corrective tasks are performed after a loss of functionality or performance of the system. (de Souza 2012, p. 124, SFS-EN 13306 2010, p. 34)

In power plants, maintenance activities should be based on preventive maintenance procedures. The maintenance history must be documented, since in most cases, it is the basis of the preventive maintenance strategy. A maintenance strategy is a strategy created for reducing the frequency and duration of service interruptions. (Diallo et al. 2009 p. 191; Woodruff et al. 2017) In large scale companies with valuable capital assets, a maintenance organization is generally responsible for the maintenance of the assets. Maintenance organizations also require supply and planning of resources, tools and spare parts to operate properly. (Driessen et al. 2015)

Boilers can be considered as high value capital assets for the operating companies. Therefore, for bigger companies in the industry, the maintenance is often handled by a service organization and the maintenance strategy is formulated by the maintenance organization. For smaller boiler operators, the maintenance strategy is often done in co-operation with the original equipment manufacturer or other companies specialized in maintenance of boilers. Formulating and conducting the maintenance strategy is crucial for the operating companies. If a power plant lacks a maintenance strategy, optimization of the equipment’s lifetime and preventing unexpected shutdowns is next to impossible. Original equipment manufacturers and specialized companies offer inspections and follow-up recommendations as a service to help companies formulate and optimize their maintenance strategy. The manufacturers and specialized companies also often offer other service works for the boilers, for example, shutdown repair and spare part supply.

Spare parts are essential for boiler operation and maintenance. In most cases, spare parts are preventive maintenance as the delivery time for boiler spare parts can in some occasions be several months. However, in a case of unexpected failure, they can also be corrective maintenance. In cases of corrective maintenance, the delivery can be as short as a few hours. Boiler spare parts can be classified into two different categories. Spare parts can either be purchased items or manufactured items for the original equipment manufacturer. Purchased items are items that are purchased from a sub supplier and manufactured items are items that are manufactured at company's own workshop. Pressure spare parts are generally manufactured by the original equipment manufacturer. These parts are typically not replaced as whole, since replacing them whole would be expensive and time consuming. Boiler pressure parts do however need maintenance. Maintenance can be done by changing worn parts of the pressure parts.

For pressure spare parts, availability is a crucial property. As the required quantity of pressure spare parts required is generally quite low, manufacturing of new material, for example tubes, is not cost efficient. Delivery time of a manufactured tube can be several months, which is in most spare part cases too long. Therefore, the optimal situation is that the manufactured tube can be found in the supplier's own or sub suppliers' warehouse. To ensure the availability, a complex of critical spare parts is often offered by the original equipment manufacturer during the sales process of a boiler. Critical spare parts are the spare parts that are necessary to ensure the operation of the boiler during the time period the spare part complex is offered for. Original equipment manufacturer can also offer recommended spare parts, but those are often offered as an option. The time period can, for example, be the same as the warranty period provided by the original equipment manufacturer.

5. TUBE BEND SPARE PART PROCESS DEVELOPMENT

In this chapter, the case study is performed on the lead time effects of the design automation system in tube bend spare part process. As the design automation system has not been created before, the chapter also includes the creation of the design automation system. Section 5.1 presents the product, tube bend, which the design automation is experimented on. Understanding of the product is necessary in order to understand the design knowledge behind the system. In section 5.2, the development project is defined. The definition includes limiting and setting the objectives for the project. After the definition, in section 5.3, design knowledge of the design process is acquired. The tube bend process is analyzed in section 5.4. The analysis includes examining the current state of the process with the help of a swimlane diagram. Section 5.5 includes the software selection for the design automation system. After the software have been selected, in section 5.6 the design automation system is created. When the system has been created, in section 5.7 the process is redefined. Finally, section 5.8 presents the piloting of the redefined process in simulated circumstances.

This chapter utilizes the general steps of process development by Martinsuo and Blomqvist (2010), presented in section 2.1, BPR implementation process by Fasna and Gunatilake (2019), presented in section 2.1.1, steps of planning a design automation system by Sunnersjö (2016) and the life cycle of an IT system by Hvam et al. (2008) presented in section 2.2.2.

5.1 Tube Bend

Tube bend is simply a tube that is bended into a specific shape. Often tube bends are supplied as spare parts for superheaters, economizers and furnace. For example, for superheaters, tube bends can be replaced as seen in figure 20.

Water, steam or both are directed through the tube bends. Therefore, as the tube bends are considered as pressure equipment, the legislation for the whole process is strict. Thus, meeting the requirements set by applicable laws is required in the whole process. These requirements must be considered in the design, manufacturing, inspection and documentation processes.

The design process of tube bends is fairly simple compared to other pressure spare parts. The design time is affected, for example by the complexity of the tube bend and the experience of the design engineer. Of the categorization by Sunnersjö (2016), presented in section 2.2.1, tube bend design process can be categorized as parametric design. As stated in section 2.2.1, the potential of design automation is highest for technologically mature products which are produced in many variants. Tube bends are mature products, which differ in almost every boiler. Therefore, according to Sunnersjö (2016), it should be possible and beneficial to utilize design automation in the design process.

5.2 Definition of the Development Project

As stated in section 1.1, the design automation system process changes are relevant only for a certain part of the process, the process in this thesis has been determined to start from the receival of the customer inquiry or lead and to end when the drawing and product data are ready and the order confirmation is sent to the customer. Manufacturing, inspections, documentation, delivery and invoicing are excluded from the process since the design automation system does not affect those processes. Possible design changes and material procurement are excluded from the mapped process as well to simplify the process mapping and design automation system creation.

The tube bend spare part process can be divided into 2 phases. These phases are the quotation phase and the delivery phase. The quotation phase starts from receival of the customer inquiry or lead and ends when the quotation is sent to the customer. The delivery phase starts from the receival of the purchase order and ends in manufacturing of the tube bend.

On the BPR categorization made in section 2.1.1, this development project can be considered as process improvement. Even though the development to the business process is quite radical, the effects can only be linked to the business process. In addition, the risks are low, the steps are incremental, and the overall effect is achieved after a long-term commitment to the re-engineering process.

Since the general description, the value chains, value networks and the process architecture have been defined earlier by the company, the objective of this development project was to map and analyze the detail tube bend process and the possible lead time effects of design automation. In this thesis, the design automation system was created and experimented on 2 types of simple bends. These bends are shown in figure 21.

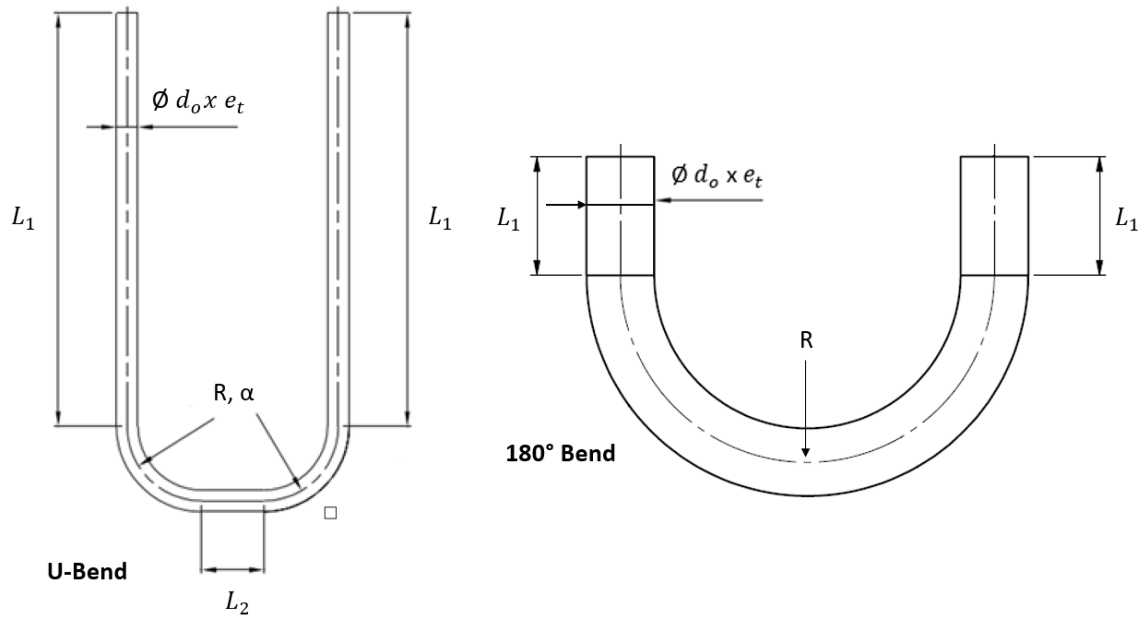


Figure 21. *Two types of simple tube bends.*

These specific tube bends, shown in figure 21, are commonly used in superheaters and economizers. More complex tube bends were excluded from the thesis, since the model and design automation system development would have taken more time.

5.3 Design Knowledge

In this section, the design knowledge required for tube bend design was gathered. Design knowledge was collected from the standard presented in section 4.4, other standards, literature and in-depth interviews. This knowledge was gathered in a table (Appendix A) to ease the process mapping and design automation system creation. Therefore, this section presents only the data required in the design automation system creation process for tube bends.

Pressure parts of water-tube boilers must be designed according to SFS-EN 12952-3. The result designs must be presented in approved drawings and definitions. Thus, the application of the standard can be ensured during manufacturing and inspection. (SFS-EN 12952-3 2011, p. 10) The manufacturer is responsible for the validity and adequacy of all calculations according to the applicable standard (SFS-EN 12952-1 2015, p. 11).

The normal procedure for pressure spare parts is that if the design is not modified from the original design, new strength calculations are not required, as the calculations have already been performed. Therefore, in this thesis the calculations and limitations regarding design are not covered if they are not required in the manufacturing drawing.

Materials that can be used for water-tube boiler pressure parts according to the standard SFS-EN 12952 are listed in standard SFS-EN 12952-2 Annex A (SFS-EN 12592-2 2011, p. 30 – 51). These materials are listed into material groups according to their chemical composition and minimum yield strength in CEN ISO/TR 15608. These material groups are shown in table 2.

Table 2. *Material groups.*

Material Group	Description
1	Steels with a specified minimum yield strength $R_{eH} \leq 460$ N/mm2 and composition of C ≤ 0.25 %, Si ≤ 0.60 %, Mn ≤ 1.8 %, Mo ≤ 0.70 %, S ≤ 0.045 %, P ≤ 0.045 %, Cu ≤ 0.40 %, Ni ≤ 0.5 %, Cr ≤ 0.3 %, Nb ≤ 0.06 %, V ≤ 0.1 %, Ti ≤ 0.05 %
4	Low vanadium alloyed Cr-Mo-(Ni) steels with Mo ≤ 0.7 % and V ≤ 0.1 %
5	Cr-Mo steels free of vanadium with C ≤ 0.35 %
6	High vanadium alloyed Cr-Mo-(Ni) steels
8	Austenitic stainless steels, Ni ≤ 35 %

These material groups are then divided into subgroups according to their minimum yield strength or chemical composition. Subgroups are shown in table 3.

Table 3. *Material subgroups.*

Subgroup	Description
1.1	Steels with minimum yield strength $R_{eH} \leq 275$ N/mm^2
1.2	Steels with minimum yield strength 275 N/mm^2 < $R_{eH} \leq 360$ N/mm^2
4.1	Steels with Cr ≤ 0.3 % and Ni ≤ 1.5 %
4.2	Steels with Cr ≤ 0.7 % and Ni ≤ 1.5 %
5.1	Steels with 0.75 % ≤ Cr ≤ 1.5 % and Mo ≤ 0.7 %
5.2	Steels with 1.5 % < Cr ≤ 3.5 % and Mo ≤ 1.2 %
6.2	Steels with 0.75 % < Cr ≤ 3.5 %, 0.7 % < Mo ≤ 1.2 % and V ≤ 0.35 %
6.4	Steels with 7 % < Cr ≤ 12.5 %, 0.7 % < Mo ≤ 1.2 % and V ≤ 0.35 %
8.1	Austenitic stainless steels with Cr ≤ 19 %
8.2	Austenitic stainless steels with Cr > 19 %

These material groups are utilized in the manufacturing planning. Material groups are, for example, used to define how the tubes should be formed and if they require a specific treatment after forming.

Forming tubes has several restrictions which can, for example be due to material or design. Tubes can either be formed cold or hot. In cold forming, steel grains are stretched in the direction of shaping, by bending this way the steel hardens. Hardness and the steel residual stress can be reduced by post-bend heat treatment or solution annealing.

In hot bending, the high temperature reduces the required force to achieve plastic deformation. (Valmet Technologies 2019) The normal procedure for bending tubes is cold bending. However, if the bending radius is small or the material is challenging to bend, hot bending might be required. Normally, the bending method is defined by the SFS-EN 12952 standard, but boiler manufacturers also have different restrictions regarding both cold and hot bending, for example due to the used bending machines or experience. In this thesis, design automation system is only created to support cold bended tube bends because most of the bends are bent cold.

Post-bend heat treatment may be required for bended tubes. Post-bend heat treatment is used to ensure that material properties are as designed after forming. Heat treatment is required for tubes with $d_o \leq 142\ \mathrm{mm}$ and $\frac{r_b}{d_o} \leq 1.3$ and for tubes with $d_o > 142\ \mathrm{mm}$ and $\frac{r_b}{d_o} \leq 2.5$. Otherwise post-bend heat treatment is not required according to the standard. (SFS-EN 12952-5, p. 26)

The standard defines 3 limitations for tube bends, which must be calculated and added in the manufacturing documentation for each manufactured tube bend. These limitations are minimum thickness at the extrados, minimum thickness at the intrados and maximum departure from circularity. Minimum thickness at the extrados e_{ext} must be defined for tubes when the outer diameter is less than 142 mm. The maximum thickness can be calculated with equation

$$e_{ext} = e_{act} \times \frac{2\frac{r_b}{d_o}+0.5}{2\frac{r_b}{d_o}+1}\ , \tag{5.1}$$

where r_b is the bending radius, d_o is the outer diameter of the tube and the nominal tube thickness minus the greatest negative tolerance e_{act} can be defined with equation

$$e_{act} = e_t - c_1, \tag{5.2}$$

where e_t is the nominal thickness of the tube and c_1 is the minus thickness tolerance (SFS-EN 12952-5, p. 22). The thickness tolerance differs in different tube standards. For example, according to standard SFS-EN 10216, the thickness tolerance for tubes with d_o ≤ 219.1 mm is ± 12.5 % or ± 0.4 mm depending on which one is greater. (SFS-EN 10216-2 2014, p. 42)

Minimum thickness at the intrados e_{int} can be calculated with equation

$$e_{int} = e_{act} \times \frac{2\frac{r_b}{d_o} - 0.5}{2\frac{r_b}{d_o} - 1}. \tag{5.3}$$

However, e_{int} is not required if the outer diameter of the tube is less than 80 mm or above 142 mm. If the outer diameter of the tube is above 142 mm, the comparison for thickening and thinning is made directly with calculated thickness given in SFS-EN 12953-3:2011, 11.3. (SFS-EN 12952-5, p. 22)

Maximum departure from circularity must be defined for all tube bends. The maximum departure from circularity u_{max} can be defined according to figure 22.

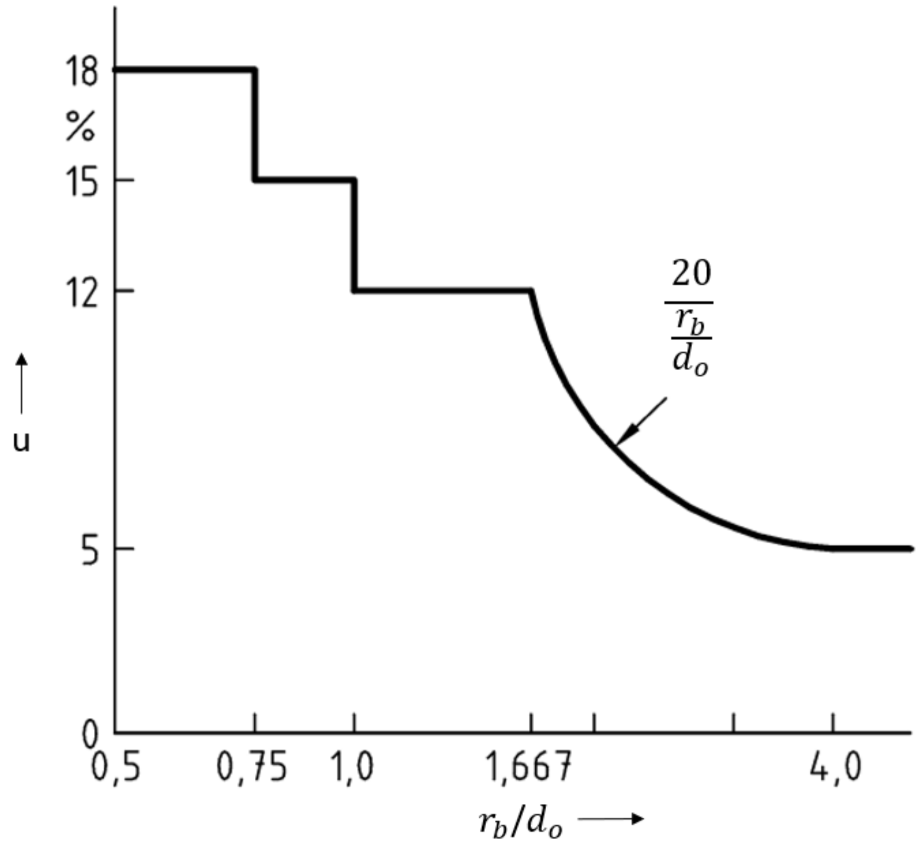


Figure 22. *Departure from circularity for double operation bending (adapting SFS-EN 12952-5 2015, p. 24).*

If the tubes are bent in single continuous operation, only the area with $\frac{r_b}{d_o} \geq 1$ of the figure is used to determine the u_{max}. If the tubes are bent by a double operation and the nominal outside diameter is less than 80 mm, the whole area of the figure is used to determine the u_{max}. (SFS-EN 12952-5, p. 24).

These calculations are required for the manufacturing to start and therefore must be included in the required design knowledge. These values are required in drawing so the manufacturing can perform the testing and inspections according to SFS-EN 12952-5 section 7.3.3. (SFS-EN 12952-5, p. 20).

5.4 Process Analysis

The objective of the process analysis phase was to identify the current state of the process. The analysis started with identifying the activities and data required in the process. First, the data required in each activity was identified and added to the data table (Appendix A). This included all of the data created during the activities of the tube bend spare part process. A part of the data table is shown in figure 23.

Data	Data From / System
Customer	Customer database
Boiler	Customer database
Required spare part quantity	Customer inquiry / lead
Required delivery time	Customer inquiry / lead
Pressure part type	Customer inquiry / lead
Assembly drawing number	DMS
Tube item code	Original design / PDM system
Tube nominal outer diameter d_o	Original design / PDM system
Tube nominal thickness e_t	Original design / PDM system
Tube material	Original design / PDM system
Tube material group	Standard

Figure 23. *A part of the Appendix A data table.*

After the data and activity identification, the departments and IT systems included in process were identified. The discovered internal departments in the quotation phase were the spare part sales, engineering and manufacturing. The external department that was required was the customer. The only IT system required in the quotation phase was the enterprise resource planning (ERP) system. In the delivery phase, the discovered internal departments were spare part sales and engineering. The external department required in the delivery phase was the customer. The IT systems that were required in the delivery phase were ERP system, computer aided design (CAD) software, document management system (DMS) and product data management (PDM) system.

When all of the data, departments and IT systems had been collected, the process mapping was possible. In this thesis, the utilized process modelling technique was chosen to be the swimlane diagram presented in section 2.1.2. The swimlane diagram was chosen as the detail process modelling tool because it illustrates the process steps, required data and systems in each stage of the process and the departments in which data is created and activities are performed. The process is quite large, and several departments are involved in the process. Therefore, use of flow diagram or data flow diagram was not optimal in this case.

The mapping of activities was essential in understanding the potential lead time effects of removing or transforming a certain part of the process. Modeling of the data was essential in the creation of an efficient design automation system. Also, when the data was analyzed, it was possible to observe whether the data creation, storage and transfer were logical and supported the process in question.

Based on the identified activities, departments, data and the design knowledge, identified in section 5.2, a swimlane diagram of the current process (Appendix B) was created. A part of the swimlane diagram is presented in figure 24.

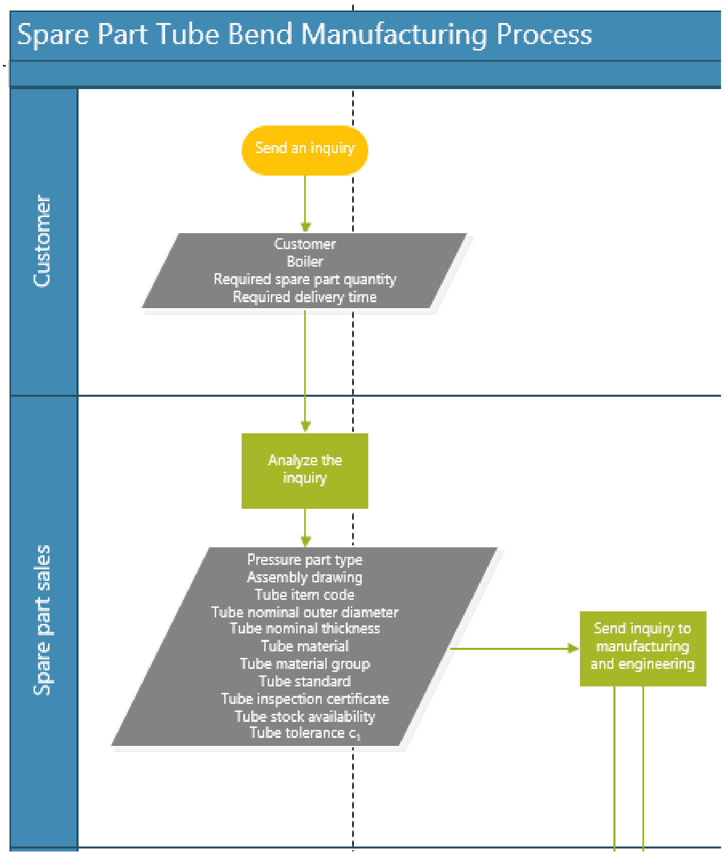


Figure 24. *A part of the Appendix B swimlane diagram.*

In the swimlane diagram, as seen in figure 24, the data created in each activity was modeled after the actual activity. The objective of the mapping was also to identify where all the data is created and stored to examine if the flow was logical. As seen in the swimlane diagram (Appendix B), the quotation phase included 8 activities and 1 IT system activity done by 3 internal departments. The delivery phase included 6 activities and 4 IT system activities by 2 internal departments.

Based on the analysis, the 3 key factors impacting the lead time of the process were individual learning, departments included in the process and the number of manual activities. Due to individual learning, more experienced employees were able to execute the activities faster. Number of departments could affect the lead time of the process if the communication between departments was slow, for example due to rush. The high number of manual activities was partly caused by lack of integrations between IT systems.

5.5 Design Automation System Software Selection

In the software selection process, 2 required IT systems were identified. These were the 3D CAD software and design automation system software. To maximize the development in lead time, the integrations between IT systems should work with as little input from the user as possible. Different options for used IT systems were considered, but the selection was impacted by the easily available systems.

SOLIDWORKS is one of the 3D CAD programs that are used in the company. Therefore, the selected 3D CAD software was SOLIDWORKS in this research. SOLIDWORKS is a 3D CAD program created by Dassault Systèmes SE. The program can be used for design, simulation, cost estimation, manufacturability checks, computer aided manufacturing, sustainable design and data management (Dassault Systèmes SE 2020a).

The basic version of SOLIDWORKS does not include a lot of possibilities for design automation. With configurations and design tables, a low level of automation can be achieved. However, for more complex models, SOLIDWORKS Application Programming Interface (API) offers more possibilities for customization and automation. The API includes hundreds of functions that can be used for automation and customization purposes in SOLIDWORKS. These functions are called from Visual Basic for Applications (VBA), VB.net, Visual C#, Visual C++ and Visual C++/CLI. (Dassault Systèmes SE 2020c)

There are also several add-ins that are created especially for design automation. Dassault Systèmes SE (2020b) lists 19 partner products, which are used for knowledge-based engineering and design automation. These add-ins ease the use of SOLIDWORKS API by providing a user interface for automating a design. In this thesis, the focus was on AutomateWorks, since it was used also in other design automation tasks in the company.

AutomateWorks is an Excel based add-in made for SOLIDWORKS. With AutomateWorks, the user can edit models by pre-determining the operations that are performed on the master model to create a customized drawing. These operations can, for example be opening and closing models, changing dimensions and attributes or printing the drawings in a PDF format. (CadWorks Oy 2020)

As AutomateWorks was chosen as the add-in to be used in the process, Microsoft Excel was an inherent choice for the user interface of the design automation system. Excel was also being used in other activities of the process. Therefore, use of Excel was familiar to the people involved in the process. This made understanding the fundaments behind the user interface easier for the user. As the time horizon was limited, a new program was not created for the design automation system in this research.

5.6 Creation of the Design Automation System

The creation of the design automation system started with a planning phase. The planning phase included defining precise objectives for the design automation system. For the draft version, the design automation system was supposed to be able to produce manufacturing drawings for tube bends with as few inputs from the user as possible. System-wise the objective was to maximize integrations with other systems for the data to be up to date and easily accessible.

When the objectives had been set, design knowledge had been acquired and the current process had been mapped, the creation of the design automation system started with creation of the master models in SOLIDWORKS. In the model creation phase, it was essential to name the dimensions so that they were easily modifiable with AutomateWorks. On this occasion, a master model was built for each type of bend presented in figure 21.

After the models had been created, drawing templates were created for both bends. The objective of these drawing templates was to include everything required in the manufacturing drawings. During this process, all the required attributes were identified for later use in the command row creation. The drawings included all the required attributes, dimensions and blocks. In this section, all the attributes were also named so that they are easily modifiable with AutomateWorks.

The first part of the actual design automation system creation in Excel was creating the AutomateWorks command row. All the modifications to the master models in SOLIDWORKS were controlled by the AutomateWorks command row. This included saving the documents, modifying dimensions, materials, attributes, blocks and running macros. As all the required modifications were not possible with just the AutomateWorks command row, SOLIDWORKS macros were also created in order to reach the desired objectives. A part of the AutomateWorks command row is shown in figure 25.

6	suppressfeat	Sweep-Thin1	TRUE
7	dimension	L1@Sketch1	500
8	dimension	L2@Sketch1	320
9	dimension	A@Sketch1	90
10	dimension	R@Sketch1	180
11	dimension	et@Sweep-Thin1	7,1
12	dimension	Do@Sweep-Thin1	60,3
13	suppressfeat	Sweep-Thin1	FALSE
14	material		Valmet Materials|16Mo3
15	attribute	Project_name	Test
16	attribute	Project_no	123

Figure 25. *A part of the AutomateWorks command row.*

After the command row had been created, a draft version of the user interface was created. The objective of the user interface was to minimize the amount of inputs inserted by the end user. By doing so, the process was sped up and there was less room for error in the user inputs. During the user input identification process, a possibility to bring tube details from the PDM system was discovered. A code for this integration already existed. With few modifications to the code by the researcher, an integration between the PDM system and the design automation system was created. This integration removed 5 user inputs. For the draft version of the design automation system, both bends were possible to create with 18-20 user inputs, which were easy for the user to find. A part of the user interface input area is shown in figure 26.

Specifications		From Original Design	
Item code		Assembly drawing no:	
Drawing number		Content (choose from dropdown list)	
Quantity / pc		Calculation pressure / MPa	
Tube item code		Max allowable working pressure / MPa	
Boiler type		Calculation temperature / °C	

Figure 26. *A part of the design automation system user interface.*

The identified calculations in the design knowledge section were also added to the design automation system. In addition, a check for hot and cold bending and heat treatment of the tube bend was added to the design automation system. These calculations and checks are presented in figure 27.

Calculations		**Heat Treatment**	
r_b / d_o	1,49	Hot / cold forming:	COLD BENDING
e_{act} / mm	6,2	PHBT / Heat Treatment	NONE
e_{int} (not required if $d_o \leq 80$ mm)	-		
e_{ext} / mm	5,4		
Maximum u / %	12,0	[redacted]	
Tube bend total length / mm	1633		
Tube Details from PDM			
Outer diameter (d_o) / mm	60,3		
Nominal thickness (e_t) / mm	7,1		
Material	1.5415		
Material group	1.2		
Tube standard	EN 10216-2		

Figure 27. *The design knowledge of the design automation system.*

In the draft version of the design automation system, integrations to other IT systems were examined. The systems which were also examined were the DMS system, ERP and customer database. The system integrations were excluded from the draft design. However, the potential of these integrations was analyzed for possible further development.

5.7 Process Redefinition

The objective of the redefinition phase was to include the design automation system in the process and to maximize the development in the lead time with the redefinition. In the analysis phase, 3 factors which affected the lead time in the process were identified. These were the individual learning, departments included in the process and the number of manual activities. Prior to the redefinition, it was presumed that modifications to these factors would have the biggest impact on the lead time of the pressure spare part process.

In the redefinition phase, the process including the created design automation system was mapped. The objective of the redefinition process was to identify activities, which can be eliminated by using the design automation system in the process. During the mapping process, some of the process activities were also redefined to supplement the redefined process. The redefinition was partly done simultaneously with the creation of the design automation system in order to identify the required data in the redefined process.

In the redefinition process, the Lean tactics and tools, presented in section 2.1.3 by Bradley (2015), were utilized. The tactics that were used were simplifying, streamlining and standardizing. From the BPR practices provided by Limam Mansar and Rejlers (2007 p. 198-199), briefly presented in section 2.1.1, contact reduction, task elimination, task composition, numerical involvement, task automation and integral technology were utilized in the redefinition process.

After the creation of the design automation system, the process was mapped again. In the mapping process, the activities, data creation and departments were redefined. Based on these redefinitions, a swimlane diagram of the process with the design automation system (Appendix C) was created.

After the redefinition of the process the quotation phase included 7 activities and 1 IT system activity performed by 2 internal departments. This meant that 1 activity and 1 internal department were eliminated from the redefined quotation phase. The delivery phase included 6 activities and 4 IT system activities, of which one was automated, by 2 internal departments. This meant that 1 IT system activity was automated, and 1 activity was replaced with a less time-consuming activity.

5.8 Process Piloting

Process piloting was carried out to ensure that the redefined process was viable and to test the lead time effects of the design automation with the redefined process. As stated in section 2.1, process piloting can be done either in simulated or real-life circumstances. Due to poor availability of real-life circumstance projects during the piloting phase, process piloting was done in comparison with completed delivery projects, which meant that the piloting was done in simulated circumstances.

The piloting phase had 2 main objectives. The first one was creating an equivalent manufacturing drawing with the design automation system as the one created by a design engineering in the actual delivery project. During the manufacturing drawing creation, the time was measured in order to calculate the achieved lead time improvement in the drawing creation process. The second one was validation of the redefined process. The validation was done in order to test if improvement to the old process could be noted. During the validation process, the lead time of the linked activities was also measured in order to understand if development in the lead time of the linked activities could be discovered.

From the existing materials, 5 different completed delivery projects that were suitable for the process piloting were randomly selected. This random selection meant that the suitability of the product was only examined during the selection process. Therefore, the data of the project was not available to the researcher prior to selection. The suitable project deliveries consisted of cold bended tube bends of either of the types presented in figure 21, that had been manufactured according to standard SFS-EN 12952.

6. RESULTS

The objective of the process piloting was to identify the lead time development of the redefined tube bend spare part process, which included use of design automation, in comparison to the old process without design automation. The process was piloted on 5 different randomly selected simulated projects. These projects were old completed delivery projects, for which the products were similar to the ones creatable with the design automation system. The researcher chose the projects prior accessing the lead time data of the projects. The decrease in the lead time of the 5 piloted projects is presented in table 4.

Table 4. *Results of piloted projects.*

	Decrease in drawing creation lead time with design automation system / %	**Estimate of the decrease in process lead time with redefined process / %**
Project 1	~ 93	69
Project 2	~ 83	47
Project 3	~ 93	69
Project 4	50	21
Project 5	~ 67	30
Average	**~ 77**	**47**

In the table, the first column shows the lead time development in manufacturing drawing creation and all related IT system activities. The second column, estimate of the decrease in the process lead time with redefined process, includes the process as defined in section 5.2 and mapped in Appendix C. As seen in the table 4, the average decrease in the drawing creation lead time with the design automation system is 77 % and the average estimate of the decrease in process lead time with redefined process is 47 %.

7. DISCUSSION

In this chapter, the results and the research process are discussed. First, in section 7.1, the results are reviewed in order to provide an insight on the significance and reliability of the results. Section 7.2 provides answers to the research questions set in the introduction chapter of the thesis. Lastly, an evaluation of the study is performed in section 7.3. This evaluation includes a review of the used research methodology, fulfillment of the objectives and limitations of the research.

7.1 Review of the Results

Business process re-engineering has produced similar results in other publications as well. Agarwal (2010 p. 117) has listed large cost savings and productivity increases by re-engineered processes. In one of the presented cases, the lead time has been reduced by 20 %. Sunnersjö (2016 p. 136) has presented a case, where the lead time of a quotation was decreased by approximately 95-97 % for a tailor-made product after the implementation of a design system. However, the system also included cost and delivery time estimation. In addition, Sunnersjö (2016 p. 138-139) has presented a case where roof rack attachment design automation system has decreased the new variant design time by 40 % and the total lead time of the process by 10 %. Lowe & Hartman (2011 p. 3) have reported a lead time development of up to 99 % after implementing a CFD design automation system. However, this publication only specifies the effects on the design process, not the whole process.

In comparison to the lead time effects presented in other publications, the results of this thesis seem reasonable. As the design process lead time decreased by approximately 77 %, it is within the results achieved in other publications. Also, the lead time development of the process, which was 47 %, is within the results of other publications. However, the defined process in this research only included a part of the whole process in this thesis. Therefore, the lead time development in the whole process is less significant.

Besides the lead time improvement, other benefits of the design automation presented by Sunnersjö (2016 p. 3-4) can also be seen in this redefined process. Creation of the design automation system does increase the quality, since the manufacturing drawing process is standardized. The design automation system also leaves time for more creative work instead of routine tube bend design assignments. These were also listed as the benefits of BPR listed by Agarwal (2010) and Zairi and Sinclair (1995) in section

2.1.1. In addition, some other benefits can be identified from the BPR process. The re-engineered process reduces the costs and increases customer satisfaction. Furthermore, the process re-engineering also has a possibility to increase the market share of the products in question.

A few sources of error possibly impacting the results can be discovered in the study. The study was affected by the researcher working in the organization where the study was performed in. Before the start of the thesis process, the researched had been working in the energy spare part team for 2 years and 7 months. This might have caused the researcher and the people concerned in the guiding process to be subjective throughout the research process. However, this has possibly also had a positive impact on the estimations performed in the piloting process.

The process piloting phase can also be a source of error. As the process was piloted in simulated circumstances, process piloting did not illustrate all the development areas in the redefined process. For example, the results do not include the decrease of required internal departments because the estimation cannot be performed based on the available data in simulated circumstances. This decrease can however be estimated to be notable at least in projects where the communication between departments is slow, for example due to rush. In addition, in the piloting phase, the design automation system, created by the researcher, was operated by the researcher. This might have had an impact on the results due to in-depth knowledge of the design automation system. For more accurate results, the system could have been operated by different people in the piloting phase in order to decrease the impact of individual learning in the estimation process.

A small sample of the piloting projects can also be a source of error. With a greater sample size, the effects of individual learning could have been balanced, and project randomness could have been increased. In this research, the randomly selected projects could have been conducted by the most or least experienced employees, which would affect the average results significantly. The selected projects can also include projects, which have encountered some issues and thus the lead time has been significantly increased in comparison to normal projects. Due to the small sample size, the effect of one distorted project is notable and therefore the results can be misrepresented.

Other publications have indicated that similar results have been achieved in similar business process re-engineering and process development processes. However, the reliability of the research may have been slightly impacted by the error sources. If the process had been piloted in real-life circumstances with greater sample size, the results would have been more reliable. The effect of these error sources on the reliability was however decreased by choosing the projects randomly without accessing the lead time data before the selection of the process. The effect of piloting in simulated circumstances was decreased by confirming the estimation from the supervisors from the company prior to estimating the results. This way the estimation was not only based on the experience and view of the researcher.

7.2 Research Questions

All the research questions set in section 1.2 were answered during the research process. These answers are presented below.

What is the current state of the pressure spare part process? (RQ 1.1)

All the required data in the tube bend spare part process are presented in a table (Appendix A). All the current process activities, software activities, data creation and departments are visualized with a swimlane diagram (Appendix B). The required data and the process are relatively the same for other pressure spare parts.

In the current state of the process, 3 notable factors that have an impact on the lead time of the process were identified. These were the impact of individual learning, number of manual activities and the required internal departments. These factors can be considered the same for other pressure spare parts.

What are the potential process changes if a design automation system is implemented? (RQ 1.2)

The process changes in several ways with the implementation of the design automation system. The number of activities, IT system activities and internal departments is decreased when the design automation system is included in the pressure spare part process. The redefined process is visualized with a swimlane diagram (Appendix C). Some of the process steps are also redefined, which means that the process step can be executed faster, which has an impact on the process as well.

How to create a design automation system that is suitable for the pressure spare part process? (RQ 1.3)

The most essential part in the design automation system creation is understanding the operation of water-tube boiler pressure parts and meeting all the requirements set by the applicable laws. The requirements can be met by following standards, which provide means of conforming essential requirements set by the laws or directives. For pressure spare parts manufactured according to PED (2014/68/EU), the SFS-EN 12952 standard provides the means of meeting the requirements.

A suitable design automation system requires a CAD software and a design automation system, which can be integrated to work together. With SOLIDOWORKS and Microsoft Excel, this can be done with the help of the SOLIDWORKS API or an add-in that has been created for design automation purposes. In the design automation system creation phase, all the required inputs must be identified and linked to SOLIDWORKS models and drawings.

In the preparation phase of the design automation system it is essential to gather the design knowledge and analyze the process thoroughly. In the design automation system creation phase, the master models and drawings should be created first. After the master models are created, the design automation system can be created and linked to the models and drawings.

How does creation of a design automation system affect the lead time of the pressure spare part process? (RQ 1)

For tube bends, the average effect on the process from the receival of the inquiry or lead to the sending of order confirmation, is approximately 47 %. For the other pressure spare parts, these results can be considered guiding. However, in other pressure parts the effect can be estimated to be greater due to the design process being more complex.

The creation of the design automation system also has some other lead time effects, which are not included in the estimation. These are caused, for example due to the need for less departments in the process.

7.3 Evaluation of the Study

All the objectives set in section 1.1 were met and all the research questions set in section 1.2 were answered. Therefore, the research can be considered successful. As the company's objective was analyzing whether redefinition and creation of a design automation system causes development in the lead time of the process, the research can also be seen successful from the company's point of view.

The scientific novelty appeal of the research is minor in comparison to the novelty appeal to the company. However, the used framework for the design automation system creation was found functional in this type of development project. When the design knowledge was gathered, and the process was analyzed and mapped prior to the design automation system creation, the required integrations, commands, user inputs and calculations were easy to define. Therefore, the research does provide a possible functional framework for design automation system creation that was created by the researcher by combining several process development and design automation system frameworks.

Issues were encountered during the research process because of a poor definition of the thesis limits by the researcher in the beginning. The objectives and research questions were changed multiple times during the process due to changes in research definition. This caused changes in the research fundaments as well. Therefore, it is recommended that the definition of the development project and objectives is done carefully in the beginning to avoid waste of time in the research phase. Nevertheless, the chosen final research fundaments were discovered to be viable for this type of research. With the use of a case study of tube bend pressure part process, guiding results for the lead time effects on all pressure spare parts was achieved. Testing design automation on all pressure spare parts was not possible within the time limits of the research process. Therefore, this was found to be the best way to test the lead time effects.

The practices and tools that were adapted from the literature for the process development, Lean, BPR and design automation system creation proved out to be functional in this type of process re-engineering. With the tools of BPR and Lean, further development in the lead time factors was identified during the redefinition process.

During the thesis process, 3 limitations were noted. The first one was the small amount of found earlier public research on similar topics. This caused the comparison of the results to the existing publications hard. However, this did not have an effect on the achieved results. The second one was the lack of real-life projects. If the piloting could have been done in real-life circumstances, while measuring the lead time at all times, the results would have been more accurate. The third one was the access to references and data. Finding reference data for simulated projects was difficult due to software changes and difference in reporting between projects. This resulted in a small number of samples in the piloting phase. In addition, due to the COVID-19 pandemic, part time lockdown of the universities prevented the use of libraries during the spring and summer. The pandemic also had an effect on the access to some data and documents while the remote work recommendations were in place. However, due to the large amount of accessible references online and the large amount of data accessible with remote connections, the effects of these limitations can be considered small.

8. ACTION PROPOSAL

In this chapter the actions based on the research are presented. First, section 8.1 presents the suggested actions for the company are listed and discussed. In section 8.2, topics for future research based on this research are discussed.

8.1 Suggested Actions

The piloting in simulated circumstances showed notable development in comparison to the old process. Therefore, piloting in real-life circumstances and implementation of the new process and the design automation system is recommended. However, in each implementation process it must be considered that both processes and IT systems require further development after the implementation. Thus, while executing the process and using the design automation system, emerged feedback is recommended to be used to develop the process and the design automation system further.

Widening the applications of the design automation system to include other common tube bend shapes, hot bended tube bends and all the possible heat treatments to the design automation system is recommended. These require small investments in resources since the design automation system for tube bends already exists.

Furthermore, widening the applications to other pressure spare parts is recommended. The effects can be presumed to be greater in other pressure spare parts as the products are more complex and the design process takes more time. However, if problems appear while applying the design automation system in other pressure spare parts, other process development options and a precise cost-benefit analysis should be carried out for the development phase to ensure payback on a reasonable time horizon.

Design automation does not only decrease the lead time of the process, but it also leaves more time for the design engineers for more creative work. Therefore, it is recommended that use of design automation is also reviewed in other design processes. If redesign of already existing and proven basic design solutions is noticed in other applications, it is recommended to analyze the possible benefits of design automation on those solutions as well.

In the design automation system creation process, a possibility for further integration with other systems included in the process was identified. Integration with customer database, ERP system and DMS would eliminate activities from the process and inputs from the design automation system user interface. Integration with the PDM system can also be developed further to decrease the amount of inputs and process activities. Therefore, it is recommended that the costs and benefits for all system integrations is analyzed. Other benefits for IT system integrations can also be found from other publications. For example, Marttila (2016 p. 71) lists less work, fewer incidents caused by human errors and a standardized product structure as indirect benefits that can be achieved by integration of a PDM and ERP system. All of these indirect benefits can also be achieved with system integrations in this occasion. In addition to analyzing the integrations, analyzing the costs and benefits of different IT system usage in this application is recommended. With different IT systems the achieved benefits can be greater.

Analyzing adding supporting features to the design automation system is also recommended. Identified supporting features, which could be integrated to the design system are manufacturing cost estimation and pricing. Adding these features to the design automation system would eliminate activities and departments from the process and therefore increase the development in the lead time.

If all the integrations and added features were possible, 6 activities, 4 IT system activities more could be automated or eliminated. After the validation of the design automation system, the design approval could also be eliminated from process requirements. Thus, the validation would eliminate 1 more activity.

Based on an estimation by the researcher, integrations, supporting features and validation would decrease the process lead time by approximately 76 % in comparison to the redefined process. This estimation does not include the development of the lead time caused by decreasing the number of departments included in the process. This development can be estimated to be notable. However, accomplishing this decrease would require significant amount of resources on the process and software development.

8.2 Future Research

As mentioned before, this research was done for a company. Therefore, the objectives were, for the most part, created to support and develop the operation of an existing specific process. Further research on the lead time effects of design automation on the pressure spare part process does not provide significant novelty value for the scientific community. However, this research can be used as a reference in other similar re-engineering processes.

Developing or creating a framework for design automation system was not an objective of this thesis. However, during the thesis process, it was discovered that a framework for such a development project could not be found. Therefore, an interesting topic would be creating a literature review on the available design automation system related frameworks. As a part of the study, due to not finding a suitable framework, a functional preliminary framework, which combined several frameworks from the literature, was also created for the design automation system creation. Interesting future research topic could be testing the framework on other similar business process re-engineering processes. By testing the framework, a validation on the functionality and possible development ideas could be discovered.

9. CONCLUSION

The objective of this thesis was to analyze the lead time effects of design automation in water-tube boiler pressure spare part process. Analysis was done by performing a case study on tube bends, which can be considered as the simplest pressure spare parts. The examined tube bend spare part process was determined to start from the receival of customer inquiry or lead, and to end when the manufacturing drawing is approved, the item in PDM system is created and an order confirmation is sent to the customer.

The case study was performed by analyzing the process before the use of design automation. As the design automation system had not been created prior to this research, it was created during the case study process. After the creation, the process was redefined to include the design automation system. When the redefinition was done, the process was piloted with and without the design automation system on 5 randomly selected projects in simulated circumstances.

Based on the projects, an average decrease of 47 % was achieved in tube bend spare part process lead time and an average decrease of 77 % was achieved in the lead time of the drawing creation process. The process re-engineering also had other impacts on the process. For example, due to the time saving in the drawing creation process, the design engineers can use the saved time for more creative work.

The difference in the process of other pressure spare parts, within the defined process limitations, is added design knowledge. Otherwise the process is nearly the same. Therefore, the results can be considered as guiding results for the use of design automation in other pressure spare parts as well. Thus, the positive lead time effects of design automation can be considered notable in water-tube boiler pressure spare parts.

Based on the results, the added customer value by the process development is inevitable. When the design of the process is standardized and the lead time is decreased, the impact can be seen, to name a few, on the satisfaction, waiting time and quality.

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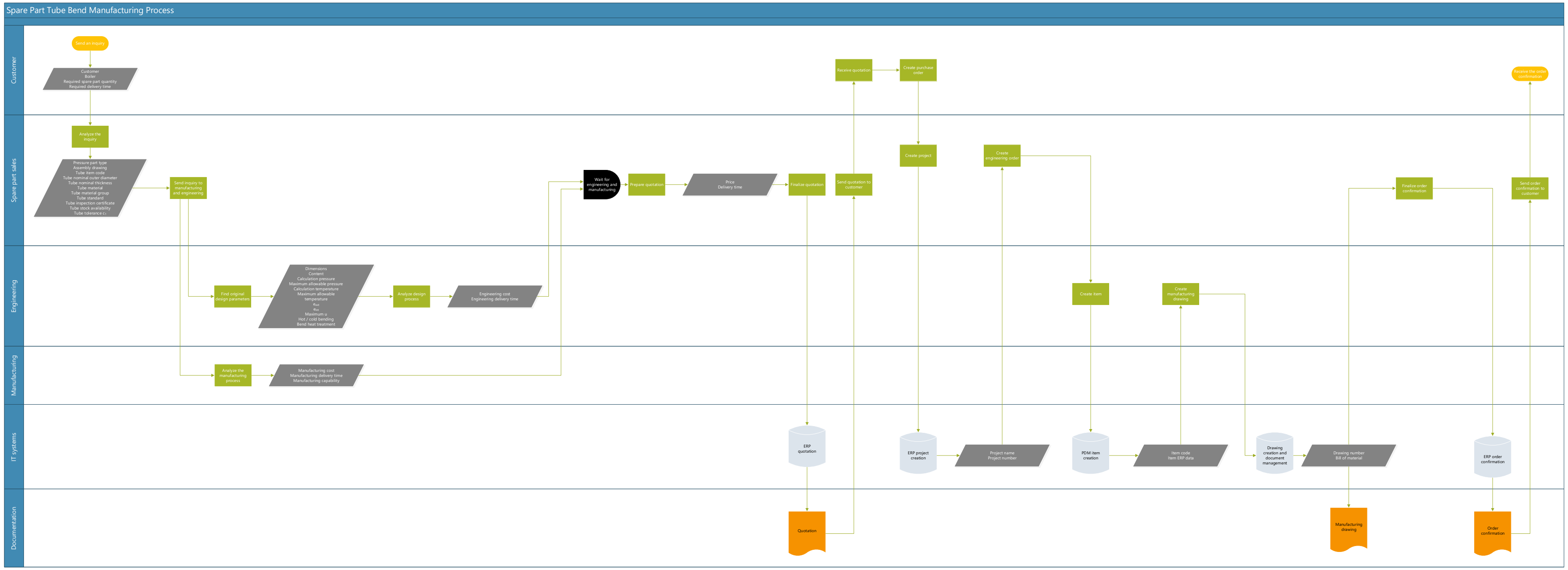
APPENDIX A: DATA REQUIRED IN THE TUBE BEND MANUFACTURING PROCESS

Data	**Data From / System**
Customer	Customer database
Boiler	Customer database
Required spare part quantity	Customer inquiry / lead
Required delivery time	Customer inquiry / lead
Pressure part type	Customer inquiry / lead
Assembly drawing number	DMS
Tube item code	Original design / PDM system
Tube nominal outer diameter d_o	Original design / PDM system
Tube nominal thickness e_t	Original design / PDM system
Tube material	Original design / PDM system
Tube material group	Standard
Tube standard	Standard / PDM
Tube tolerance c_1	Standard
Tube inspection certificate	Standard / PDM
Manufacturing cost	Manufacturing responsible
Manufacturing delivery time	Manufacturing responsible
Manufacturing resource availability	Manufacturing responsible
Engineering cost	Design responsible
Engineering delivery time	Design responsible
Price	Quotation responsible
Delivery time	Quotation responsible
Project name	ERP
Project number	ERP
Dimensions	Original design
Content	Original design
Calculation pressure	Original design
Maximum allowable working pressure	Original design
Calculation temperature	Original design
Maximum allowable temperature of the contents	Original design
e_{ext}	Standard
e_{int}	Standard
Maximum u	Standard
Hot / cold bending	Standard
Bend heat treatment	Standard
Drawing number	DMS
Bill of material	CAD
Product item code	PDM system
ERP data	PDM system

APPENDIX B: A SWIMLANE DIAGRAM OF THE TUBE BEND MANUFACTURING PROCESS WITHOUT A DESIGN AUTOMATION SYSTEM



APPENDIX C: A SWIMLANE DIAGRAM OF THE TUBE BEND MANUFACTURING PROCESS WITH A DESIGN AUTOMATION SYSTEM